AO 98-OSS-03	Explorer Program, Medium-Class Explorers (MIDEX) and Missions of Opportunity

Principal Investigator			
Dr.	**Kenneth**	**John**	**Johnston**
Title	First Name	Middle Name	Last Name

Department

Astrometry Department

Company/Institution

United States Naval Observatory

Street Address	City/Town
3450 Massachusetts Ave., N.W.	**Washington**

State	ZIP/Postal	Country
District of Columbia	**20392-5420**	**USA**

Telephone	Fax	E-Mail Address
(202) 762-1513	**(202) 762-1461**	**kjj@astro.usno.navy.mil**

Principal Investigator's Signature	Date
Kenneth J Johnston	8/18/98

Proposal Title

Full-Sky Astrometric Mapping Explorer (FAME)

Abstract

FAME is a space astrometry mission that offers the unique opportunity to measure the positions, proper motions, parallaxes, and photometry of 40,000,000 stars brighter than V=15th magnitude to unprecedented accuracy. The astrometric accuracy will range between 30 and 300 microarcseconds, dependent on the magnitude. The instrument will rotate in a scanning survey pattern similar to the *Hipparcos* project. The spacecraft will be geosynchronous with the precession primarily driven by solar radiation pressure. The resulting data will provide a definitive calibration of absolute luminosities of "standard candles" for defining distance scales, calibrate the absolute luminosities of solar neighborhood stars, provide a definitive determination of the frequency of solar-type stars orbited by brown dwarfs and giant planets, provide proper motions and distances for individual stars in star-forming regions, assess the abundance of dark matter in the galactic disk, and become an astrometric and photometric catalog. This mission is a complement to, and source of input data, for the Space Interferometry Mission (SIM).

Institutional Endorsement

Name of Authorizing Official

Dr. Kenneth J. Johnston

Title

Scientific Director

Address

United States Naval Observatory, 3450 Massachusetts Ave., N.W. Washington, D.C. 20392-5420

Signature	Date
Kenneth J Johnston	8/18/98

FACT SHEET

Full-Sky Astrometric Mapping Explorer

FAME

Dr. Kenneth J. Johnston, US Naval Observatory, Principal Investigator

Science Objectives. FAME will measure the positions, proper motions, parallaxes, and four-color magnitudes of 40 million stars brighter than 15th visual magnitude during the observational program. The positional accuracy will be the finest yet achieved. The positional, parallax, and proper motion accuracies will be better than 50 µas, 50 µas, and 50 µas/year, respectively.

❏ We will calibrate the absolute luminosities of "standard candles" that define the distance scale to galaxies. This supports the Origins, and Structure and Evolution of the Universe themes.

❏ We will calibrate the absolute luminosities of hundreds of solar-neighborhood stars for studies of stellar evolution. This supports the Origins, and Structure and Evolution of the Universe themes.

❏ We will detect large planets, planetary systems, brown dwarfs, and stars with non-linear proper motions that are not single star systems. This supports the Origins, and Solar System themes.

❏ We will study kinematic properties of stars and assess the abundance of dark matter in the galactic disk. This supports the Structure and Evolution of the Universe theme.

Mission Overview. The FAME spacecraft will be placed in a geosynchronous orbit, with a rotational axis 45˚ from the Sun, rotating with a 20-minute period. The rotational axis will precess around the Sun every 10 days. FAME will sweep the sky repeatedly, in a pattern similar to the *Hipparcos* project. The mission life is 2.5 years, with a potential extended mission life of 5 years.

Science Payload. The scientific instrument has a compound mirror looking in two directions separated by an angle of 65˚. The two fields of view are combined on a focal plane with 20 astrometric charge coupled detectors (CCD) and four photometric CCDs. The CCD readout rate is maintained at the spacecraft spin rate providing integration time for the observations. The pixels with stellar images are read out, time tagged, and transmitted to the ground station.

Key Spacecraft Characteristics. The spacecraft is a 3-axis spin stabilized vehicle with a prescribed motion fitted with a solar radiation shield to generate the correct precession rate. Thus, the sky is observed in a continuing spiral pattern. The spacecraft's thrusters reset altitude, spin rate, and perform stationkeeping maneuvers as necessary. The geosynchronous altitude enables the spacecraft and the ground station to communicate continuously.

Mission Operations. The Ground Station includes a control center, a dedicated 10 m antenna, and a Science Data Processing Center. These facilities are linked to an alternate command and control antenna site and to NASA's communications system.

Anticipated Launch Vehicle. Delta 7425.

Mission Management. The U.S. Naval Observatory (USNO) will manage the mission, science, and data processing. Lockheed Martin Missiles and Space (LMMS) Advanced Technology Center will build the instrument. The Naval Research Laboratory (NRL) will build and integrate the spacecraft and provide a backup ground station. The Infrared Processing and Analysis Center (IPAC) will process and analyze photometric data. The Smithsonian Astrophysical Observatory (SAO) will provide technical support. Omitron Inc. will provide the primary ground station located at USNO.

Schedule.

Phase A	January-April 1999
Phase B	June 1999-February 2000
Phase C	March-October 2000
Phase D	November 2000-February 2003
Launch	March 2003
Phase E	April 2003-October 2005
Extended Mission	2008

Cost Estimate. $138M ($FY98)

FACT SHEET

Full-Sky Astrometric Mapping Explorer

FAME

QUICK FACTS

Spacecraft, Launcher, and Orbit	
Launcher (to GTO, 28.7 degree inclination)	Delta 7425
Launch capability at GEO	1132 kg
Apogee Kick Motor	Star 30BP
Orbit	Geosynchronous (GEO) 35786 km
Instrument Mass	165 kg
Total Spacecraft mass and Contingency w/AKM	961.6 kg
Mission Lifetime	2.5 years
Instrument	
Effective Focal Length	7.5 m
Number of Apertures	2
Aperture Size	0.50m x 0.25m, each
Primary Mirror Size	0.56m x 0.56m
Focal Plane Scale	0.0275 arc-sec/micron
Airy box size at nominal wavelength (600nm)	0.5 arc-sec (1.2 pixels)
CCD Size	2048 x 4096 pixels
Pixel Size	15 microns
Pixel on Sky	0.413 arc-sec
Rotation Period	20 minutes
Precession Period	10 days
Rotation Rate	2618 CCD rows/sec; 0.382 msec per row
Time for star to traverse a CCD	1.56 sec
No. of amplifiers per CCD	2
Mean angle between Sun and spin axis	45 degrees
Drift of star due to precession	< 4 pixels/CCD crossing
CCD Binning	1 x 5
CCD readout rate per amp after binning	536 kHz
Number of Astrometric CCDs, Total	20
Number of Astrometric CCDs with Neutral Density Filters	3
Number of Photometric CCDs	4
Photometric Bands	Sloan g’, r’, i’, z’
ADC	3 at 12 bit (staggered)
No. of times a star is observed (astrometric)	4000
No. of times a star is observed (photometric)	1080
Instrument Performance	
Wavelength Range	400 to 900 nm
Magnitude Range (mv)	5 - 15
Astrometric Accuracy (positions and parallaxes in µas; proper motions in µas/yr.)	50 for V < 9, 300 for V < 15
Photometric Accuracy	1 millimagnitude

Table of Contents

Table of Contents (Continued)

List of Figures

List of Tables

1. Science Goals and Objectives

1.1 Science Description.

1.1.1 Mission Goals. FAME will accurately measure, to 10% error or better, the absolute trigonometric parallaxes (i.e., the distances), positions, and proper motions, as well as the apparent magnitudes, of stars brighter than 9^{th} visual magnitude that lie within 2.5 kpc of the Sun. Results of this survey will definitively address five key scientific objectives having far-reaching astrophysical and cosmological significance:

❏ Definitive calibration of the absolute luminosities of the "standard candles" (the galactic Cepheid variables and the RR Lyrae stars) that are fundamental in defining the distance scale to nearby galaxies and clusters of galaxies;

❏ Calibration of the absolute luminosities of solar-neighborhood stars, including Population I and II stars, thus enabling diverse studies of stellar evolution and other interesting science. In the case of Population II subdwarfs, this will allow the determination of the distances and ages of galactic and extragalactic globular clusters with unprecedented accuracy;

❏ Definitive determination of the frequency of solar-type stars orbited by brown dwarf companions in the mass range 10 to 80 Mjup and with orbital periods as long as about twice the duration of the mission. This will include an exploration of the transition region between giant planets and brown dwarfs, which appears to be in the range 10 to 30 Mjup;

❏ Proper motions and distances for individual stars in star forming regions for determinations of ages and kinematics; and

❏ A study of the kinematic properties of the survey of 4 x 10^7 stars within 2.5 kpc of the Sun, and in particular, assess the abundance and distribution of dark matter in the galactic disk with much greater sensitivity and completeness than previously possible.

The proposed investigation will also provide a catalog of star positions, proper motions, and colors that will meet spacecraft navigation, guidance, and attitude control needs of the United States Department of Defense (DOD) and NASA.

The volume of space included in the survey is large enough to contain significant numbers of all classes of stars found in the Milky Way Galaxy

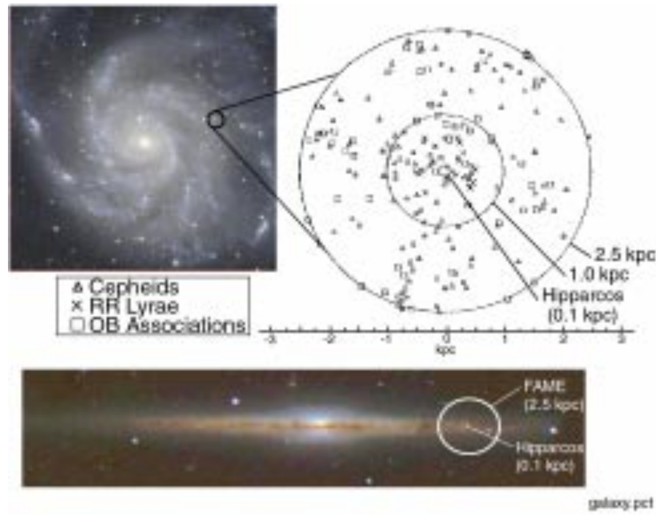


Figure 1-1. Hippacros and FAME Observation Coverage in the Milky Way

(see Figure 1-1). The survey will provide the scientific community with an invaluable and durable resource that will support a large number of other significant and fundamental, astrophysical investigations, beyond the few to be addressed within the immediate scope of the proposed investigation.

1.1.2 FAME Contributions to NASA Themes and Strategic Plan. FAME will provide the positions, proper motions, parallaxes, and photometry of all stars as faint as 15^{th} visual magnitude with accuracies of 50 microarcseconds (μas) at 9^{th} visual magnitude and 300 μas at 15^{th} visual magnitude. It will provide vital and fundamental astronomical data that address key questions of three NASA themes:

❏ For Origins, FAME will provide (a) the distance scale for the standard candles, (b) knowledge of stars in the solar neighborhood, and (c) detection of hundreds of substellar companions to solar-type stars, with a definitive exploration of the transition region between giant planets and brown dwarfs and the identification of prime targets for further research with SIM and TPF.

❏ For Structure and Evolution of the Universe, FAME will provide (a) knowledge of stellar properties of our galaxy, (b) distance scale for the standard candles, (c) accurate reference for Gravity Probe B, (d) distribution of matter in the disk of our galaxy, and (e) an understanding of how both dark and luminous matter determine the geometry and fate of the universe.

❑ For Solar System, FAME will (a) detect or help identify other planetary systems, (b) help understand how stars and other planetary systems form together, and (c) provide a very accurate reference frame for solar system observations.

The results of the FAME project will contribute to the NASA Strategic Plan by helping to answer the fundamental questions of “how did the universe begin and what is its ultimate fate?” and “how do galaxies, stars, and planetary systems form and evolve?” FAME fits into the following strategic plan science goals: (1) understand how both dark and luminous matter determine the geometry and fate of the universe; (2) understand the dynamical and chemical evolution of galaxies and stars and the exchange of matter and energy among stars and the interstellar medium; and (3) understand how stars and planetary systems form together. FAME will help fulfill the following strategic plan scientific objectives: (1) measure the amount and distribution of dark and luminous matter in the ancient and modern universe and (2) observe and characterize the formation of stars, protoplanetary disks, and planetary systems, and detect Neptune-size planets around other stars. FAME will complement and support SIM and TPF in fulfilling the strategic program for 2000-2004 goals to: (1) understand how both dark and luminous matter determine the geometry and fate of the universe and (2) understand how stars and planetary systems form together.

In addition, for all themes and all astronomy, FAME will provide the most accurate reference frame ever obtained.

1.1.3 Relationship to Other Missions and Ground Observations. FAME is a small, low-cost survey instrument to determine the positions, proper motions, parallaxes, and photometry of 40,000,000 stars from 5th to 15th visual magnitude with 50 μas accuracy at 9th visual magnitude. It will greatly expand upon the observations of the successful *Hipparcos* satellite. It will help define positions for SIM grid stars, identify candidate stars for SIM and TPF, and complement the observational program of the pointed SIM instrument, which can observe about 10,000 stars at 4 μas. SIM science center and FAME personnel will be involved in data reduction procedures that have some commonality. There will be early identification of relevant techniques and reusable software. FAME will give an additional temporal baseline for SIM observations.

FAME will be launched at least 5 years before the proposed GAIA mission. In addition, DIVA, a proposed German mission with similar goals to FAME, but with reduced size, cost, and capabilities, is planned to be a second epoch *Hipparcos*. Neither DIVA nor GAIA are currently funded.

FAME vastly surpasses ground-based astrometric programs. The best wide-field accuracies from the ground are achieved by optical interferometers, which can reach 1 milliarcsecond (mas) accuracy for about 50 stars per night. There are no astrometric optical interferometers in the southern hemisphere. Narrow field accuracies of hundreds of μas can be achieved by interferometers and special instruments on very large telescopes for only a small number of stars. Ground-based survey instruments using charge coupled devices (CCDs) can at best achieve 25 mas relative accuracies. Thus, there is no current means of achieving a full-sky survey of millions of stars at microarcseconds accuracies other than by a space instrument.

1.2 Objectives and Significant Aspects.

1.2.1 Background. Our most fundamental knowledge about stars (their masses, absolute luminosities, distances, and motions in three-dimensional space) rests ultimately and inevitably upon direct measurements of the apparent places of stars relative to a frame of reference ideally defined as an inertial rest frame. From such measurements over time, we can derive the trigonometric parallaxes (the reciprocal of distance measured in parsecs), as well as the proper motions (the annual change in apparent place caused by a star’s movement perpendicular to the line of sight). When the speed of motion along the line of sight is also known from spectroscopic measurement, the space velocity of a star is fully defined. In the case of binary stars, this information can yield the masses of the components. These parameters are basic to our knowledge of stellar structure and evolution, the structure and dynamics of the galaxy, and the scale of cosmological distances.

Prior to CCD development, trigonometric parallaxes could only be measured photographically (with ground-based telescopes) to within an accuracy of about 10 mas, corresponding to an uncertainty of 10% at distances of 10 parsecs. The best modern ground-based measurements, using CCD detectors, achieve accuracies of about l mas, (Monet et al. 1992), pushing the limit of accurately known stellar distances out to about 100 parsecs. These are relative parallaxes as they are measured with respect to background stars. *Hipparcos* measured absolute parallaxes to l.5 mas, independent of background stars.

Measurement of relative parallax down to 20-30 μas can be achieved with ground-based optical interferometers over narrow fields. However, when these measurements are converted to absolute parallaxes, the final accuracy is not better than about 1 mas because distances and surface characteristics of the not-very-distant background reference stars are unknown. Very high accuracy (10-20 μas) measurements of absolute parallax are achieved in differential radio interferometry over small angles. Both these measurements are necessarily limited to relatively small numbers of objects.

Accuracies of 1-10 μas (yielding distances to 10% accuracy from 10 kpc to 100 kpc) would be achieved in the optical measurement of absolute parallax by proposed space missions such as SIM in the United States and GAIA in Europe. These missions will cost over $500 million each, and would logically follow FAME in the middle to later part of the next decade.

FAME, as a survey mission, complements the pointed mission, SIM. A survey mission will catalog a very large number of stars ($>10^7$), while a pointed mission of 5 year duration will study at most 10,000 objects very accurately. A survey mission such as FAME will yield knowledge on stars with excellent statistics, seeing as far in the galactic plane as extinction permits. The large number of stars will also allow corrections for reddening along the line of sight to program stars such as Cepheids and RR Lyrae via cluster main sequence fitting. The resulting data set will greatly expand our knowledge of the basic parameters of stars, the building blocks of galaxies and the universe. This knowledge will lead to fundamental advances in galactic astronomy and cosmology.

1.2.2 Specific Objectives. It is in this context that we see the opportunity for a MIDEX-class mission to make a definitive contribution to the solution of a number of very far-reaching problems in astrophysics and cosmology by providing accurate absolute parallaxes of 4×10^7 stars out to 2.5 kpc (25 times the current distance limit and over 15,000 times the volume of space for ground-based wide-field astrometry and *Hipparcos*), as shown in Figure 1-1. This volume is sufficient to contain significant numbers of all classes of stars, including Cepheid variables, RR Lyrae and δ Scuti stars, O, B and A stars, and Population II subdwarfs, as well as star-forming regions such as the Orion Nebula, as shown in Foldout 1, Figure FO 1-3. Compelling reasons to undertake such a mission at this time can be cited in the context of several disciplines in astronomy and astrophysics. The key objectives we propose to address specifically and definitively in this mission are described in the following:

❏ *Fundamental Calibration of the Absolute Luminosities of RR Lyrae Stars and Galactic Cepheids, the "Standard Candles" for Measuring Cosmological Distances:* The period-luminosity relation for Cepheid variables, and the luminosity-metallicity relation for RR Lyrae stars, are fundamental to the determination of distances to the galaxies in nearby clusters and thus, ultimately, to the determination of the expansion age of the universe (c.f. Madore & Freedman 1991). Despite the fact that these stars have been used as distance indicators for a great many years, their calibration in absolute units is still very much an issue. See Foldout 1, Figure FO 1-3 for FAME's coverage.

- *Cepheids.* Although the slope of the period-luminosity relation for Cepheids is known from observations in the Magellanic Clouds, the zero-point of the relation must be derived from Galactic Cepheids. Such a zero-point derivation is currently uncertain by 10-20%, since the distances of Galactic Cepheids (with the exception of Polaris) are beyond reach of current capabilities for measuring trigonometric parallaxes. Instead, indirect methods are used (c.f. Evans 1995, 1992; Jacoby et al. 1992; Feast & Walker 1988). FAME will measure the absolute parallax of a significant sample of Cepheid variables directly, and thereby obviate all of the traditional, intermediate calibrations. Feast and Walker (1988) give a list of cluster Cepheids, and Foldout 1, Table FO 1-4 shows the SNR that FAME will deliver. With FAME-determined parallaxes, field Cepheids can also be used as primary distance calibrators. This increases the number of calibrators, and provides many more of the long-period Cepheids that are of most value in measuring distances. Foldout 1, Table FO 1-1 lists field Cepheids within 1 kpc and the expected SNR that FAME will provide. This rich sample of Cepheids with accurate distance determinations will be the basis for a calibration of the period-luminosity relation, and for the investigation of possible three-parameter relationships.

- *RR Lyrae Stars and Globular Clusters.* The ages of globular clusters give a lower limit to the age of the universe and hence provide an important constraint on cosmology. At present, however, the ages are uncertain by about 30%, primarily because the distances are uncertain by 15% and age scales are the inverse square of the distance. Several methods support the "short" RR Lyrae distance scale (M_V (RR) ~0.75 at [Fe/H]= -1.6) including statistical parallaxes of RR Lyraes and kinematic distance to clusters. Main-sequence fitting of *Hipparcos* subdwarfs supports the "long" distance scale (M_V (RR) ~0.45). Baade-Wesselink and theoretical methods can support either scale depending on assumptions. (See Popowski & Gould 1998 for a comprehensive review.) The long scale is roughly in agreement with the standard Cepheid scale, which currently stands at the base of the extra-galactic distance ladder (van den Bergh 1995).

FAME will definitively measure M_V (RR) by obtaining accurate (<10% error) trigonometric parallaxes to 21 nearby RR Lyraes, Foldout 1, Table FO 1-2. Assuming an intrinsic dispersion of 0.14 mag in absolute magnitude, this will determine M_V (RR) to 0.04 mag (2% in distance).

In addition, FAME will lay the basis for two direct checks on this fundamental measurement. First, FAME will measure proper motions of ~500 halo RR Lyraes within 3 kpc. If radial velocities are measured for these, they will yield a statistical parallax solution for M_V (RR) accurate to 0.06 mag. While not as robust as trigonometric parallax, statistical parallax is more nearly free of systematic errors than other currently used methods (Gould & Popowski 1998) and is currently limited primarily by the smallness of the sample.

Second, FAME will obtain trigonometric parallaxes with smaller than 5% errors to approximately 250 metal-poor subdwarfs. These can be matched to main sequence stars of similar metallicity in globular clusters to independently measure their distances. Reid (1997) and Gratton et al. (1997) have applied this method to a much smaller and less precisely measured sample of *Hipparcos* subdwarfs and obtained results that support the "long" distance scale. If the FAME determinations of globular cluster distances from subdwarf and RR Lyraes are in agreement, then the conflict over the RR Lyrae distance scale will be resolved. If not, it will demonstrate that there is something fundamental that we do not understand about either subdwarfs or RR Lyraes. In either case, the present rather murky state of the globular-cluster distance scale will be cast in a clearer light.

❑ *Determination of the Local Mass Densities:* A catalog of relative velocities of stars to 15th magnitude would, of course, have a vast number of uses over many years. We plan to use this catalog to investigate definitively the distribution of mass as functions of height above the galactic plane and of galactic radius. In particular, we will determine the local mass density and the local surface mass density of the galactic disk.

This relates directly, within the volume of space included in the survey, to the long-standing and apparently universal issue of missing mass or "darker matter" implied by dynamical studies of galaxies and galaxy clusters. The one place where there is a complete inventory of the luminous stars is in the immediate neighborhood of the Sun. From the mass-luminosity relation (determined from observations of binaries), we know the total mass in these stars and hence the total mass density of luminous material in the neighborhood of the Sun. What we do not know is the total mass density. If the total mass density were substantially greater than that of the luminous matter, this would demonstrate the existence of significant disk dark matter. Because disks are formed by dissipation, such dark matter would almost certainly be baryonic. Detection of baryonic dark matter would be a clue to the nature of the dark matter overall and would greatly constrain our models of external galaxies.

Most previous measurements of the local mass density relied on stellar radial velocity and density measurements in a cone perpendicular to the galactic plane. The results have differed by up to a factor of 2 (Bahcall 1984; Kuijken & Gilmore 1989, 1991; Bahcall et al. 1992; Flynn & Fuchs 1994) most likely because of systematic errors. Crèzè et al. (1998) pioneered a radically different type of survey based on *Hipparcos* proper motions of ~3000 nearby stars and found that the local mass density is almost completely accounted for by visible material. However, because *Hipparcos* was complete only to V < 8, they were able to probe only within 100 pc of the Sun. Moreover, since they were mainly restricted to bright (and hence young) A and F stars, it is possible that their sample was not dynamically mixed.

FAME will provide an estimate of the local density of matter (which can be directly compared with the local density of stars and gas) that is essentially free of systematic error, by measuring proper motions within 30˚ of the galactic plane. A study based primarily on proper motions is to first order free of systematic errors because the quantity to be determined (i.e., the disk epicycle frequency $\omega = \sqrt{4\pi G\rho_0}$) and the quantity being measured (i.e., proper motions) have the same units (1/time).

FAME will measure accurate proper motions (< 4km s^{-1} kpc^{-1}) of N ~ 10^5 early G stars with distance < 500 pc and |b|<30°. The resulting transverse velocity errors (<2 km s^{-1}) are small compared to the stellar motions, so this will allow a measurement of ρ_0 to a 3% error.

This G dwarf study will be the anchor point of the FAME attack on this problem, but many other classes of stars can also be used. For example, K giants can be used to probe at much greater distances from the plane (because accurate proper motions and parallaxes can be measured at much greater distances). In addition, F and A stars can give a very detailed look at the mass distribution close to the plane because of their low velocity dispersion. Even though these stars are not dynamically mixed, in the large volume probed by FAME the phase inhomogeneities of many unconnected subsamples will tend to cancel, permitting the use of these stars.

In brief, FAME will improve on the pioneering *Hipparcos* study of local dark matter by almost one order of magnitude in distance and two orders of magnitude in numbers of stars. It will also be less susceptible than the *Hipparcos* study to systematic errors caused by phase inhomogeneities.

❑ *Giant Planets and Brown Dwarfs:* Radial velocity surveys of several hundred nearby solar-type stars have discovered a few dozen unseen companions with minimum masses below the substellar limit, in the mass range 0.5 to 80 Mjup. Most of these have orbital periods shorter than 5 years. An analysis of the secondary mass distribution for low-mass companions suggests that the frequency of stellar companions (i.e. brown dwarfs) drops off rapidly near the substellar limit, while the frequency of giant planets rises toward lower masses (Mazeh et al. 1998). The transition region between giant planets and brown dwarfs appears to lie in the range 10 to 30 Mjup, although this result is still very preliminary and uncertain because of the small number of systems available for the analysis.

FAME will provide a definitive determination of the frequency of solar-type stars orbited by brown dwarf companions in the mass range 10 to 80 Mjup and with orbital periods up to about twice the duration of the mission. This will include an exploration of the transition region between giant planets and brown dwarfs. To be specific, FAME has the sensitivity to derive orbits for companions with masses down to 8 Mjup around 24,000 solar-type stars within 100 pc, 4 Mjup around 3,000 solar-type stars within 50 pc, and 2 Mjup for 375 of the nearest solar-type stars within 25 pc. These numbers are based on the results from simulations carried out for the GAIA mission (Casertano 1998), adapted to the FAME mission parameters of 50 μas astrometric accuracy.

In addition, FAME will be able to derive orbital inclinations for many of the stellar and substellar companions with spectroscopic orbits, thus eliminating the sin(i) ambiguity in the masses determined from the spectroscopic orbits. For the 51 Peg type systems with hot Jupiters in short-period orbits, FAME will be able to search for additional companions in much wider orbits. The discovery of additional companions would be especially significant, because it would provide evidence for planetary systems (as opposed to just the largest planet) orbiting solar-type stars, which is something that has not yet been accomplished.

❑ *Star-Formation Regions:* The nearest star-formation regions in our galaxy lie at a distance of 150 pc (e.g., Taurus-Auriga), and the nearest rich star-formation region lies at 450 pc (Orion). The stars in these regions were mostly too faint to be observed by *Hipparcos*. The improved sensitivity of FAME will allow large numbers of pre-main-sequence stars in these regions to be surveyed. Perhaps the most important result will be to provide distances to individual stars, thus allowing them to be placed accurately on an HR diagram. This is critical for the determination of better ages of individual pre-main-sequence stars, which are presently uncertain by about a factor of 2 or more.

Furthermore, accurate proper motions provided by FAME, together with ground-based radial velocities, will allow studies of the kinematics of star-formation regions, which will clarify the process(es) by which newly-formed stars are distributed into the disk of the galaxy.

In particular, FAME will investigate the membership of many young (~10^6 yr old) galactic clusters. ROSAT observations have shown that many of these clusters are surrounded by large populations of X-ray sources in extended halos up to several degrees in size. These extended X-ray populations can outnumber cluster X-ray T Tauri stars by a factor of 10, so it is very important to determine whether they are also young stars that formed at the same time as the compact clusters. Knowing whether or not these stars are members of the clusters will fundamentally impact our knowledge of the mass function in galactic clusters, the lifetime for accretion disks and planet formation, and dynamical evolution of young clusters. FAME observations of these bright stars (V ~ 11 mag for M ~1 solar mass at the distance and age of the Chamaeleon cluster) will determine whether the compact clusters are at the same distances as their extended X-ray populations, and FAME tangential velocities will reveal whether the extended populations could have traveled from the cluster cores over the cluster lifetime (as deduced from its stellar evolutionary ages).

Finally, FAME will be able to determine the orbital inclinations of selected pre-main-sequence binaries with spectroscopic orbits, thus contributing to our knowledge of the masses for pre-main-sequence stars. There are at present no direct mass determinations for pre-main-sequence stars less massive than the Sun.

❑ *Other Science:* The data collected will serve as an invaluable resource in the public domain that will inevitably bring significant progress to other fields of astronomy. For example, stellar models require accurate observational constraints on stellar luminosities, masses, and radii as input. The accuracy required for luminosity is ~1%, for which parallaxes must be known to 0.5%. FAME will measure parallaxes to 0.5% accuracy for stars brighter than 12^{th} magnitude in a sphere of 20-pc radius.

FAME will reach 1% relative precision for the luminosities of a sizable number of main sequence A and F stars. This group is especially interesting because it includes the transition from radiative to convective energy transport in the outer envelope, and many stars with peculiar characteristics such as Ap and pulsating δ Scuti stars. With metallicities obtained by spectroscopy, very precise determination of the luminosity will allow fundamental parameters to be derived, such as the depth of the convective zone and the efficiency of convective transport. For cooler stars, precise luminosities will place strong constraints on other fundamental parameters, such as the equation of state and molecular opacity. At a 5% level of accuracy, the distance horizon will include rarer but important types of stars, such as O stars, supergiants, T Tauri stars, Cepheids, and RR Lyrae stars.

Our knowledge of stellar masses derives mainly from the analysis of binaries. FAME will determine parallaxes and relative positions of the components of binaries, thus contributing significantly (in terms of accuracy and the number of binaries with known orbits) to the determination of stellar masses. Perhaps the most significant contribution will be for stars less massive that the Sun. In the range 0.08 to 0.5 solar masses there are only two double-lined eclipsing binaries that have been published, both of which yield masses to better than 1%. All the other masses for M dwarfs, about 2 dozen, rely on astrometric orbits and are less accurate by about an order of magnitude. FAME will provide orbital inclinations for nearby M dwarf binaries with double-lined spectroscopic orbits, thus contributing significantly to the number of low-mass stars with accurate masses. When supplemented by ground-based metallicity determinations, this will allow critical tests of models of stellar structure and evolution for low-mass stars, which are now only poorly constrained. Through analysis of the positions of photocentric emission and the use of multiple colors, FAME will likewise determine the masses in unusual systems such as those containing white dwarfs and black holes.

FAME will provide accurate parallaxes for the determination of absolute dimensions in the cases where angular sizes are known. Only a few accurate radii are presently available for testing stellar models, the best of these coming from the analysis of eclipsing variables. Ground-based interferometry and lunar occultation techniques typically measure angular radii to accuracies in the range 0.2 to 2.0 mas. Future ground-based instruments, such as the Navy Prototype Optical Interferometer, will have the capability to measure stellar diameters and shapes (and their time variation) to 0.1 mas.

Likewise, FAME will contribute fundamentally to calibrating the distances to open star clusters, determining the absolute color-magnitude diagrams of newly-formed star clusters, and identifying candidate stars for the possible detection of planets. FAME will measure the gravitational bending of starlight by Jupiter, Saturn, and the Sun, allowing the post-Newtonian deflection parameter to be determined with significantly better accuracy than currently available.

The photometric observations using the Sloan Digital Sky Survey filters (Foldout 1, Figure FO 1-1) will detect many variable stars, provide significant improvements for HR diagrams, improve knowledge of stellar populations, and provide corrections for use in astrometric reductions.

1.3 Investigation Approach. The *Hipparcos* project was the first astrometric survey ever conducted without the limitation of Earth's atmosphere. It measured more than 100,000 stars to an accuracy of 1 mas and had a magnitude limit of V=12. Through advances in technology, FAME will dramatically improve upon the sensitivity and accuracy of *Hipparcos*. Measuring over 40 million stars to better than 50 μas ($V < 9$) and having a magnitude limit of V=15, FAME will expand the measurement space by over three orders of magnitude (see Figure 1-1).

Much like *Hipparcos*, FAME is based on the use of a telescope that looks at two FOVs separated by a fixed basic angle (65 deg). The spacecraft rotates at a rate of once every 20 minutes and measures stars along a spiral. Foldout 1, Figure FO 1-4 illustrates the rotational observing technique. The rotation axis of the spacecraft precesses around the Sun direction (35 times a year) to scan the whole sky. Foldout 1, Figure FO 1-2 illustrates the scanning pattern. Unlike *Hipparcos*'s image dissector tube, FAME will use a modern CCD array with high quantum efficiency to determine transit times while simultaneously observing many stars. The CCDs will be used in a time-delayed integration (TDI) mode to synchronize the readout with the rotation of the spacecraft. Modern instrumentation coupled with advances in the design and construction of low-cost, lightweight spacecraft will make FAME very cost effective with a high science return. The FAME mission concept, instrument, and spacecraft are discussed in Section 2.

An input catalog will be generated by the science team using data from the Washington Comprehensive Catalog Database and other USNO catalogs. The input catalog is required to "window" the pixel data. The accuracy needed is 0.5 arcseconds, which will be easily attained using USNO catalogs. The catalog will be loaded onboard the spacecraft and will be re-programmable after launch. Over the course of the 2.5-year mission, each of the program stars will be scanned in different directions over 4000 times. The data from all the targets will be analyzed in order to derive their positions, proper motions, parallaxes, and colors. The data will be analyzed using procedures and algorithms somewhat similar to those used in the *Hipparcos* data reduction (see Section 2.3).

Foldout 1, Table FO 1-3 lists the predicted astrometric accuracy for FAME based on the estimated error budget. The accuracy has three components: systematic errors, detector read noise, and photon noise. Systematic errors, arising from instrument limitations (such as pixel variations) will limit performance for bright stars (For the brightest stars, the limiting factor is fewer observations due to the use of neutral density filters). We have calculated a systematic error floor of 10 μas. For faint stars, the dominant error source is 7e$^-$ CCD read noise. Between these extremes, the dominant error source for stars between 10th and 14th visual magnitude will be photon noise. See Section 4.3.1 for a discussion of the error budget.

1.3.1 Baseline Mission. The FAME baseline mission is 2.5 years of continuous observations, interrupted by orbit, attitude, and rotation adjustments, as necessary. The observations will include astrometric observations in the regular CCDs, bright star observations through neutral density filters, and photometric observations through four filters. The instrument will observe 40,000,000 stars in the magnitude range $5 < V < 15$ with mission positional accuracies between 30 and 300 μas and photometry with milli-magnitude accuracies. The parallaxes and proper motions will be of equivalent accuracy.

1.3.2 Extended Mission. The baseline mission described in this proposal is for a 2.5 year lifetime. However, there are significant advantages to extending the mission. Increasing the length will increase the number of observations on the target stars and hence the resulting astrometric accuracy. Position and parallax measurements will improve as the square root of the mission length, whereas proper motion measurements would improve as the 1.5 power, thereby producing a catalog whose star positions are accurate for a longer period of time. The detections of low mass companions and giant planets are also significantly improved by the longer mission. Since this catalog is important for DOD applications, operations for an extended mission would be paid for by the Navy.

1.4 Minimum Science Mission. The FAME science team has determined that the science return from a mission, which is half as astrometrically accurate as that shown in Foldout 1, Table FO 1-3, would remain compelling and exciting. With an accuracy of about 80 μas for all objects brighter than 9th magnitude, the number of Cepheids that could be measured to 10% would decrease from 20 to 5. Though a serious impact to this science objective, FAME will still provide the first direct absolute parallax measurements on these targets. For RR Lyrae stars, the impact is less; half of the objects in Foldout 1, Table FO 1-2 can still be measured to 10% error.

Although a minimum science version of FAME will still measure 40 million or more stars, decreasing the performance by a factor of two will reduce the volume of stars for a given accuracy by 8. Our survey would still exceed previous capability by a factor of 10, measuring stars accurately within a 1 kpc radius. Again, this would result in poorer statistics in the study of Population II subdwarfs and other classes of stars. However for all but the rarest stellar types, the sample will still contain an abundant numbers of stars.

1.4.1 Descopes. The definition of the minimum mission is given in 1.4. At any time during Phases A, B, and C, the PI can take descope action to resolve otherwise insoluble problems. However, if descopes are used to develop or replenish reserves, they have to be planned and executed on a carefully thought-out schedule. This section addresses descope options that could be executed to increase funding available for the future conduct of the project, or to terminate developments when funds for the task are depleted.

❑ *Astrometric Accuracy Descope.* The minimum science requirement for astrometric accuracy allows degradation of the following parameters:

- The number of observations per star reduced by a factor of 4, or
- A decrease in the electronic signal-to-noise factor of 4, or
- Change to a lower orbit and lack of transmission of all data, or
- Reduction in the number of CCDs.

These parameters are not independent. Degradations in all will convolve to determine the net degradation:

- Performance associated with the number of observations per star acquired depends only on system architecture (memory sizes, data rates, number of CCDs, etc.) and can be calculated.
- Signal-to-noise is determined primarily by the CCD behavior. Experience with devices similar to the FAME CCDs gives confidence that the noise specification can be met.

Descopes in astrometric accuracy to build cost reserves by reducing the number of CCDs must be made early in the project. Changes in the orbit and launch vehicle can be made later in the program and result in reduction of launch vehicle cost and loss of observational data.

Table FO 1-1. Field Cepheid Variables Within 1 kpc

Star	Period		Distance	
	(day)	<V>	(kpc)	SNR
DT Cyg	2.50	5.78	0.45	44
FF Aql	4.47	5.38	0.45	44
BG Cru	3.34	5.47	0.45	44
RT Aur	3.72	5.42	0.50	40
YSgr	5.77	5.75	0.59	34
TVul	4.43	5.75	0.63	32
V1334 Cyg	3.33	5.85	0.67	30
AHVel	4.23	5.68	0.67	30
AX Cir	5.27	5.85	0.71	28
IR, Cep	2.11	8.60	0.71	28
R Tra	3.39	6.66	0.71	28
U Aql	7.03	6.47	0.77	26
MY Pup	5.70	5.65	0.77	26
U Vul	8.00	7.14	0.77	26
EW Sct	10.00	8.01	0.77	26
S Cru	4.69	6.57	0.83	24
S Sge	8.37	5.66	0.83	24
Y Oph	17.14	6.15	0.53	24
BFOph	4.06	7.28	0.91	22
VCen	5.49	6.82	0.91	22
T Cru	6.73	6.59	0.91	22
TU Cas	9.14	7.65	0.91	22
V636 Sco	6.79	6.66	0.91	22
BB Sgr	6.64	6.99	1.00	20
EU Tau	2.10	8.15	1.00	20
RV Sco	5.47	7.05	1.00	20

Table FO 1-3. Estimated Error Budget Totals

Visual Magnitude	Accuracy (μas)
5	29
7	48
9	15
11	30
13	76
15	226

Table FO 1-2. RR Lyrae Stars with Parallax Measurement Errors <10%

Star	Period		Distance	
	(day)	<V>	(kpc)	SNR
RR Lyr	3.69	8.57	0.25	80
XZ Cet	2.83	9.20	0.38	52
CS Eri	2.05	9.20	0.48	42
MT Tel	2.07	9.28	0.48	42
AE Boo		10.00	0.56	26
UV Oct	3.49	9.79	0.56	27
V429 Ori	3.17	10.00	0.59	24
DH Peg	1.80	9.78	0.63	23
XZ Cyg	2.93	10.53	0.63	16
RR Cet	3.57	10.33	0.63	18
x Ari	4.48	10.48	0.63	16
RZ Cep	2.04	10.31	0.63	18
RX Eri	3.86	10.10	0.67	20
VX Scl		10.50	0.67	15
SU Dra	4.58	10.24	0.67	18
TU Uma	3.61	10.24	0.67	18
SWAnd	2.77	10.76	0.67	12
VInd	3.02	10.48	0.71	14
TT Lyn	3.96	10.17	0.71	18
DX Del	2.97	10.26	0.71	16
SVEri	5.17	10.23	0.71	16
DN Aqr	4.31	10.50	0.71	14

Table FO 1-4. Cluster Cepheid Variables

Star	Period		Distance	
	(day)	<V>	(kpc)	SNR
SU Cas	1.95	5.97	0.26	76
SZ Tau	4.03	6.53	0.59	34
U Sgr	6.74	6.70	0.63	32
V Cen	5.49	6.82	0.67	30
S Nor	9.75	6.42	0.91	22
T Mon	27.02	6.13	1.67	12
H0144972	5.10	8.87	1.69	12
CPD-537400	11.22	8.37	1.69	12
RZ Vel	20.40	7.09	1.72	12
WZ Sgr	21.83	8.03	1.75	11
DL Cas	8.00	8.97	1.79	12
RS Pup	41.39	7.01	1.79	11
RU Sct	19.70	9.4	2.04	10
VY Car	18.93	7.46	2.08	10

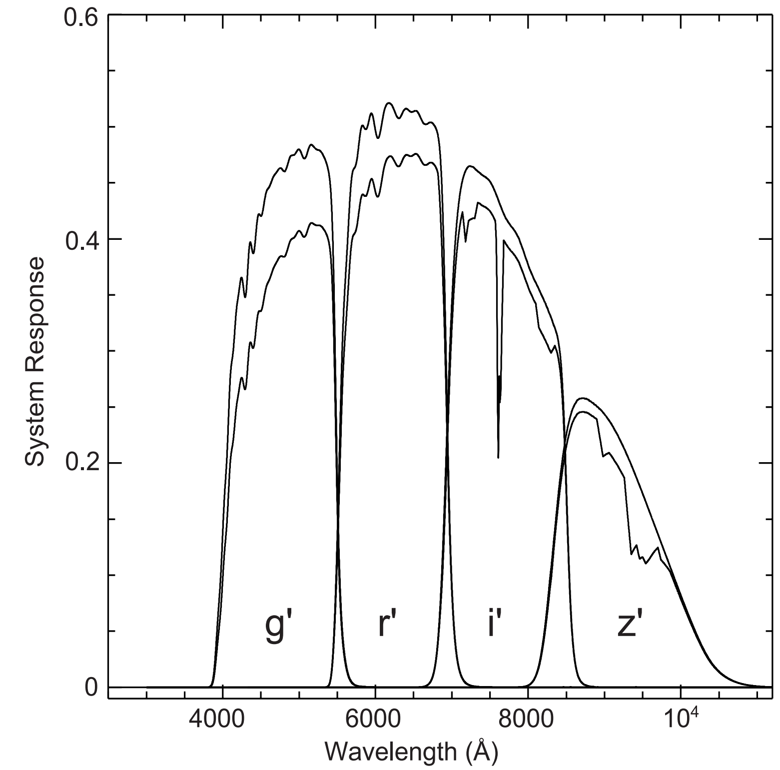


Figure FO 1-1. Sloan Filter Set With & Without Atmosphere

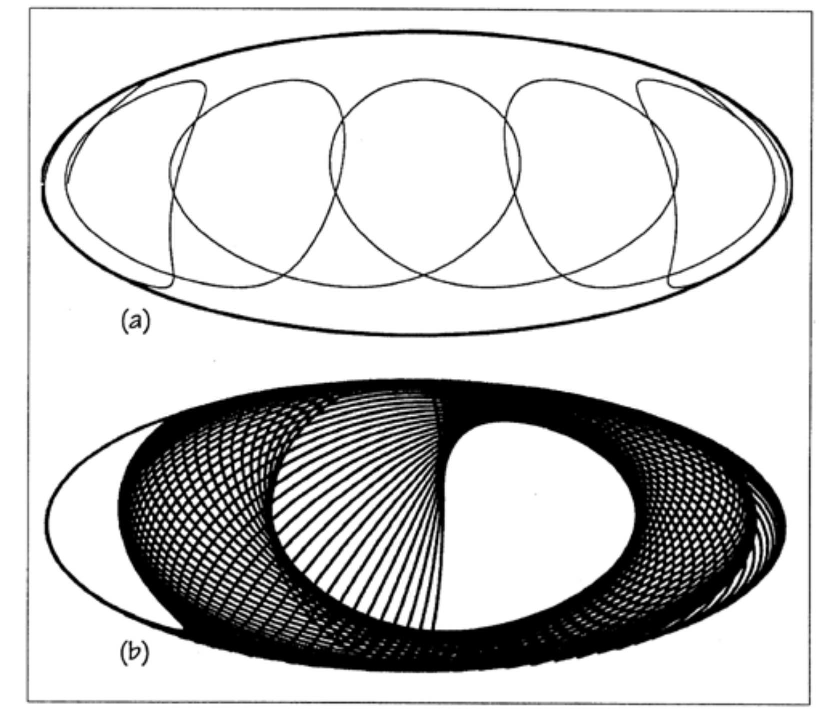


Figure FO 1-2. FAME Scan Strategy

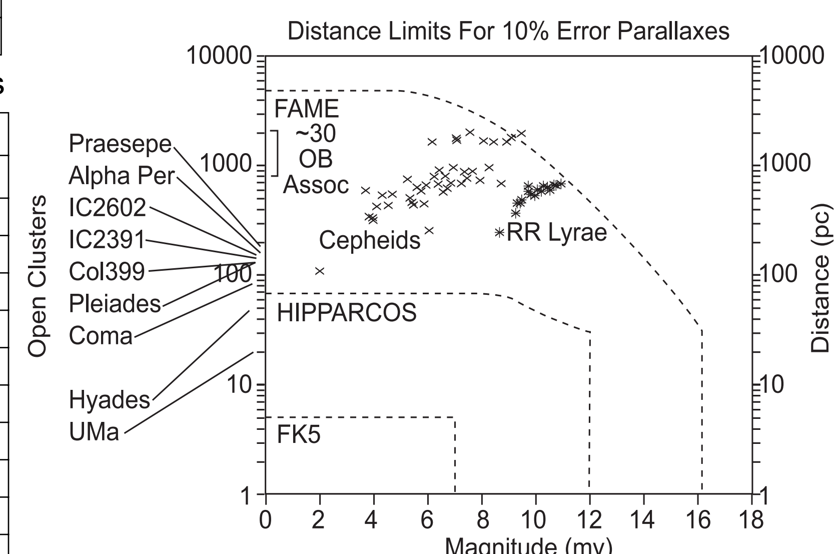


Figure FO 1-3. Stellar Distances vs. Magnitude for Selected Science Targets

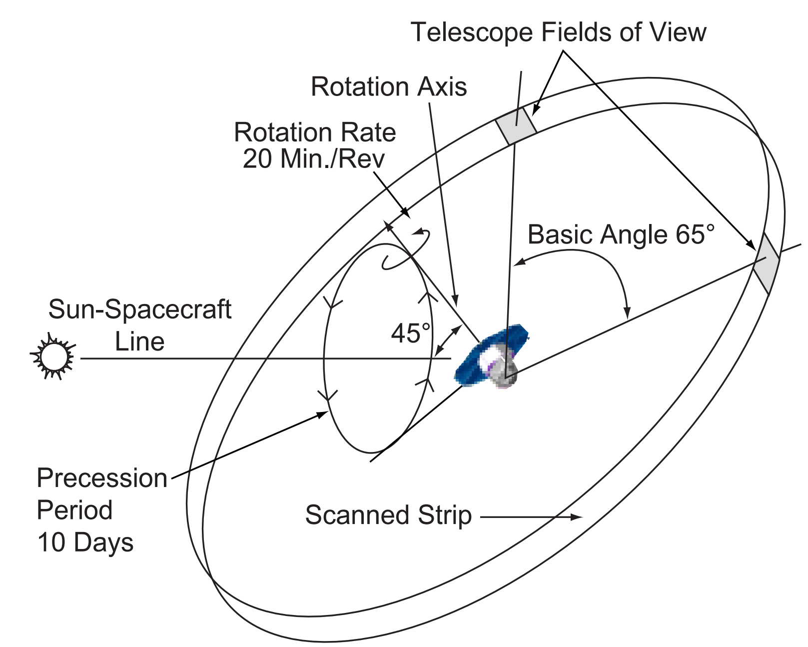


Figure FO 1-4. FAME Observing Concept

2. Science Implementation

2.1 Instrumentation.

2.1.1 General Overview. The FAME instrument payload is shown in Foldout 2, Figure FO 2-1. The optical ray trace is shown in Foldout 2, Figure FO 2-2. The optical system images two different fields-of-view (FOV) onto a large-format CCD mosaic camera. Instrument electronics control and read out this camera and digitize the pixel output. Field Programmable Gate Arrays (FPGAs) window the digitized CCD output around stars listed in the on-board input catalog. The instrument central processor combines the windowed data from the 24 FPGAs and timing information into a single data stream that is transferred to the S/C to be queued for telemetry to the USNO Control Center. The instrument electronics also control the temperatures of the optics and their support structures. Lockheed Martin Missiles and Space (LMMS) Advanced Technology Center in Palo Alto is teamed with USNO, NRL, and SAO to design, construct, test, and support the instrument.

2.1.2 Instrument Architecture. The present instrument architecture is the result of a two-year study that started with an earlier version of FAME and the heritage of the successful ESA mission, *Hipparcos* (Perryman et al. 1989). The main results of the study are documented in a pair of SPIE papers (Reasenberg & Phillips 1998; Phillips & Reasenberg 1998). FAME takes from *Hipparcos* its two essential geometric characteristics, (1) two widely separated FOVs that are combined on a single detection plane, and (2) a scan pattern that involves both a nominal spin axis orthogonal to the look directions and precession of that spin axis around the Sun direction. The architectural study yielded seven principal results that lead us to the present FAME design. The "information rate" described below is the sum of the inverse variance of the position measurement of the observed targets per unit time. The seven results are:

a. A central obscuration of the telescope has minimal effect for this instrument;

b. The aspect ratio of the pupil (here the beam-combiner mirror) does not affect the information rate, which is proportional to the pupil area;

c. Smooth instrument rotation improves the absolute astrometric accuracy;

d. Solar radiation pressure (instead of thrusters) can precess the S/C smoothly;

e. For a focal plane of fixed size, and over accessible values of the effective focal length, F, the information rate varies slowly with F, and favors a small F;

f. There are many possible values for the basic angle. For instrument design, a basic angle of 65˚ for the baseline design is selected; and

g. The *Hipparcos*-type scanning pattern gives good (complete but not uniform) sky coverage, independent of the angle (ξ) between the Sun direction and the nominal rotation direction.

Based on results a and b, a square primary mirror is used to facilitate packaging. Results c and d lead to a preference of smooth rotation, and precession by the action of radiation pressure. The traditional *Hipparcos* rotation rate (2.5 hrs per rotation) requires a fine adjustment of the shape (sweep-back angle) of the solar shield to reduce the radiation pressure torque (by about 1.5 orders of magnitude) to an appropriate level. With the (seven fold) faster rotation of FAME, the full torque of a nearly flat shield is used, and therefore a simple mechanism can be used. Result e includes the effects of two conflicting factors. Assuming a fixed number of pixels: i) the field of view is proportional to F^{-2} and ii) with a shorter focal length, there are fewer pixels over the diffraction pattern; note that the centroid is less precise (in the high-signal case). Combined with results c and d and additional considerations, result e directed us toward a fast rotation and short focal length. Result f permits us to set the basic angle to 65˚ for convenient packaging, superior thermal control, and enhanced baffling. Result g confirms a well advertised aspect of the *Hipparcos* mission; astrometric results do not depend importantly on the nominal value of ξ or its change over the mission lifetime.

2.1.3 Instrument Description.

❑ *Optics:* Phillips and Reasenberg (1998) describe the FAME optical ray trace Foldout 2, Figure FO 2-2 in detail, including the prescription. The beam-combiner mirror is composed of two 0.5 m x 0.25 m flats, which accept two FOVs separated by the 65˚ basic angle, and is the system aperture stop. These two fields are sent into the remainder of the optical train, a three mirror anastigmat, which images them coincidentally on its final focal plane. The square primary mirror (0.56 x 0.56 m) sends light to a circular secondary, which is near the center of the beam-combiner mirror. This secondary mirror forms an intermediate image, which is located near the fold flat in front of the primary. This flat sends the light to the tertiary, which forms a pupil at the location of this same fold flat. The rays from the tertiary pass through a central hole in the fold flat and a hole in the primary before striking a second fold flat (behind the primary). The rays are then imaged onto the detector. The design has an effective focal length of 7.5 m, delivers diffraction-limited performance, and has very low distortion (0.005%) over the entire field imaged by the detector, Foldout 2, Figure FO 2-3.

All elements are made of ultra-low expansion (ULE) glass and are lightweight. For ease of manufacture, conic sections are specified for all three powered surfaces (primary, secondary, and tertiary). The beam-combiner mirror consists of two ULE wedges, bonded together by optical contacting at their common surface. LMMS developed the optical contacting technique for large surfaces for the Stanford Gyro Experiment (the Gravity Probe B test of general relativity). Stray light is minimized by baffles made of 0.8 mm Al.

Several vendors (Kodak, Zygo, Arizona) have determined that the optics can be readily manufactured and have provided quotations.

Optics are aligned in several stages. First, the vendor's interferometric testing ensures that each mirror meets its requirements. The vendor registers the mechanical and optical axes of each mirror to within 70 microns, facilitating high-quality, initial, mechanical alignment. The primary mirror is mounted on the optical bench and aligned mechanically. The structure supporting the beam-combiner and secondary mirrors is then installed. An autocollimating test flat and interferometer are used to align the secondary mirror. Finally, the beam-combiner mirror is added. The relay system, consisting of the tertiary mirror, the fold flats, and a test CCD at the focal plane are then be added, aligned, and focused. The entire optical train is tested with an external light source and a scan mirror to simulate S/C rotation. The science focal plane detector assembly is added once optical wavefront quality is measured and verified at all focal plane locations. Optical performance is verified with the science focal plane in place. Next, the system undergoes thermal vacuum and vibration tests before final acceptance tests and delivery.

❑ *Structure:* The mechanical structure comprises an optical bench and subassemblies that hold the mirrors and detector assembly, Foldout 2, Figure FO 2-1. All structural elements are made of a graphite cyanate (GrCyn) material. This material is fabricated into a laminate that has a near-zero (about 10^{-7}/K) 2-D coefficient of thermal expansion (CTE), matching the CTE of the ULE optics at 300 K. Precise CTE matching was demonstrated (at 300K and low temperatures) as part of the Next Generation Space Telescope (NGST) prototype primary mirror demonstrator. All panels (bench, detector, primary, beam-combiner, and tertiary mirror support structures) are constructed of discrete rib cores, egg-crated together, and covered by outer skins with a 2.5 mm wall thickness. All mirrors are kinematically mounted with Ti flexures.

The primary mirror assembly is mounted on a strong-back structure that also supports the detector assembly. The beam-combiner mirror assembly is kinematically mounted to a strong-back structure that also supports the secondary and tertiary mirror assemblies. The tertiary mirror assembly is structurally stiffened by a GrCyn panel (with ribbed core) that connects to the primary mirror strong-back structure.

The secondary mirror cell is mounted through a hole in the beam-combiner mirror assembly and attached to its strong-back bulkhead. The first fold flat protrudes through the primary mirror and is suspended by a 1.4 mm wall GrCyn ribbed tube that attaches to the rear of the strong-back bulkhead. The second fold flat cell and detector is mated rigidly to the optical bench by a GrCyn adapter, and the detector camera head is fixed to the top panel of the strong-back structure.

❑ *Thermal Design:* The instrument's high measurement precision is achieved without using laser metrology (along with its associated cost and risk) by combining stable, low CTE, materials and multi-layer thermal control. The first thermal control layer, a flat solar shield, prevents sunlight from directly reaching the instrument. Further, the shield temperature distribution is invariant under

S/C rotation around the spin axis. During the rotation cycle, the small heating of the instrument by reradiation from the back of the shield does not change. The optics and structural temperatures must be maintained between 10 and 20˚C, the temperature region in which the materials have low and matched CTEs.

The instrument is isolated from the S/C by Ti and G10 (fiberglass) flexures and a 20 layer MLI blanket on the underside of the optical bench. The instrument structure is surrounded by an Al frame structure coated with a 20 layer MLI blanket. This blanket reduces both variable heating by Earth and radiation to space, which would otherwise need to be replaced by electrical power. The instrument optics view space over approximately 0.4 m^2 through the star view ports and their associated baffles. The port baffles are insulated and thermally regulated to just above their equilibrium temperature to minimize both the heat loss and the variable heating effect of the Earth on the instrument.

The structure and mirror backs are heated to 290 K with electric resistive heaters; this temperature corresponds to broad minima in the CTEs of the ULE optics and GrCyn structure. This heating requires 150 W of electrical power in steady-state operation to balance the radiative losses to space. This power is reduced by using approximately 30 W of heat generated by the detector preamp.

Several events produce thermal disturbances at different times in FAME's rotation and orbit cycles. Solar input goes to zero during eclipses. Eclipses last a maximum of 70 min and occur once per orbit (day) during two seasons a year; each season lasts approximately 5 weeks. The heating of the instrument by the Earth also varies due to the 20 min rotation period, and the greatest disturbance is caused when the Earth passes directly through both star view ports on a single rotation. This occurs in roughly 15% of FAME rotations and is dependent on the slowly changing angle between the S/C orbital plane and satellite axis of rotation. Other disturbance sources, like the moon, are small compared to the Sun and Earth and are not considered.

We have modeled these effects on the temperatures and astrometric performance of the FAME instrument. This model included both solar and Earth thermal disturbances experienced by FAME. Results show that during most FAME observations, the thermal disturbances caused by varying solar and Earth heat loads on the FAME radiation shields cause only minuscule changes in the temperatures of the instrument. Foldout 2, Figure FO 2-4 shows the static temperatures and gradients of the optics for the nominal configuration of FAME in its orbit at the subsolar point. In this configuration, even with the instrument heaters running at fixed power, the instrument temperature at any point changes by no more than 1 mK during a single 20 min rotation period. Such a temperature change yields an unmeasurable (less than the single-measurement uncertainty) shift of the stellar images on the detectors.

In the most extreme thermal configuration, the Earth passes directly through both fields and deposits approximately 10 W m^{-2} into the star view ports. Without thermal regulation, this configuration raises the instrument temperature less than 10 mK in one 20 min rotation period and by approximately 100 mK in steady state. However, thermal regulation will ensure that no part of the FAME instrument optics or structure will change temperature by more than 5 mK from its nominal value (see Foldout 2, Figure FO 2-4**)** at any time.

❑ *CCD Detector Camera Head:* FAME's excellent astrometric performance is due largely to its large-format, focal plane camera. Twenty 4096 x 2048 pixel astrometric CCDs are located in a mosaic covering 2.2 deg^2 in the FAME focal plane (Figure 2-1). Three astrometric CCDs are covered with neutral density filters (shaded in Figure 2-1) that extend the system dynamic range. Four additional science-grade photometric CCDs are located just outside of the astrometric CCDs in a region of slightly poorer image quality. These photometric CCDs are each covered with 2 of the different Sloan passband (g', r', i', and z') filters (each filter covers half of the columns).

Lockheed Martin Fairchild Systems (LMFS), under the direction of R. Bredthauer, produces the FAME CCDs. These are minor modifications of existing LMFS CCD 485 devices that have 4096 x 4096 square 15 micron pixels. Modifications consist of optimizing the response, reducing the size of the shift registers, geometry, and horizontal summing well sizes. The spaceflight heritage of

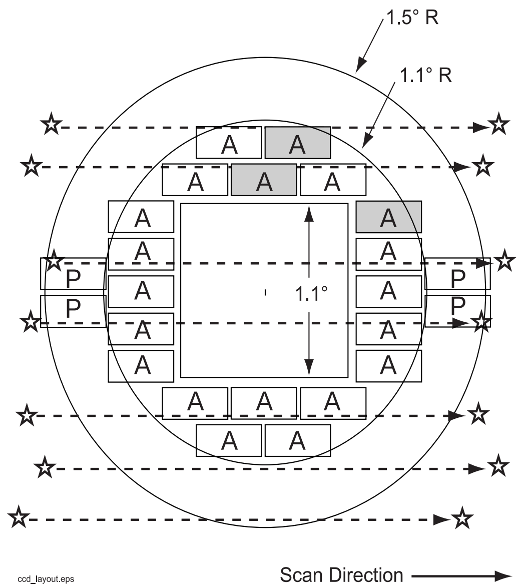


Figure 2-1. Layout of CCDs in Focal Plane

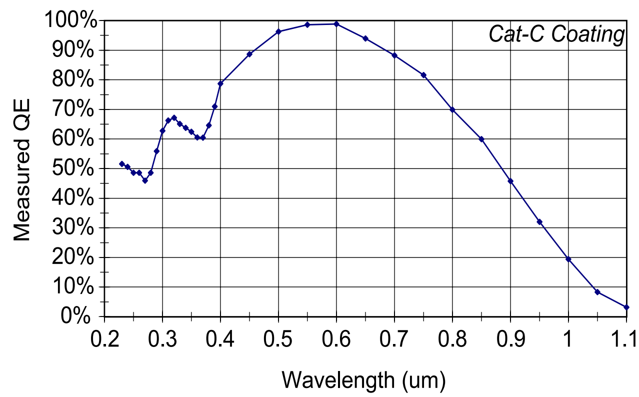


Figure 2-2. QE Curve of LMFS CCDs

Table 2-1. FAME CCD Specifications

Format	4096 x 2048 backside-illuminated
Pixel Size	15 x 15 microns
Process	3 phase buried channel, notch, multi-phase pinned (MPP)
Fill Factor	>99%
Output Amps.	2 on-chip
Amp. Sensitivity	3 microVolt / e-
Quantum Efficiency	≥ 90% at 600 nm
Noise	7e- RMS at 500,000 pixels s^{-1} read-out frequency
Dark Current	<25 pA at 20˚C
Charge Trans eff	0.999995
Pixel Full Well	>100,000 e- MPP
Serial Full Well	>450,000 e-

these devices includes the *Cassini* camera. CCDs using the same proprietary process are also used in the LMFS Autonomous Star Tracker (LAST). The FAME CCDs are three side buttable and have two output amplifiers. The science does not require that the chips be butted at the ends. Device thinning and coating is done by LMFS using technologies transferred from the Steward Observatory CCD Laboratory (M. Lesser). Very high quantum efficiencies are further enabled by state-of-the-art anti-reflection coatings (Figure 2-2). Table 2-1 lists nominal device specifications. We will optimize device geometries during Phase A.

The 4096 columns on each CCD are clocked in a TDI mode at 2.7 kHz to keep each star's charges under its image as it crosses each chip in 1.6 seconds. Groups of 5 pixels are binned in the cross-scan (orthogonal to TDI) direction, which is less critical for astrometry. This binning reduces the ADC rate five-fold and reduces read noise by a factor of >2.2. Little information is lost since S/C precession (an essential aspect of the scanning law) smears the image over a maximum of 4 pixels (3 pixels RMS) in the cross-scan direction.

The CCD camera head assembly is constructed of a composite GrCyn face sheet with a honeycomb core. CCDs are individually bonded to boards in small mosaics of two to five chips. All GrCyn surfaces exposed to the CCDs are Ni plated to prevent emission of contaminants. The neutral density and photometric filters are mounted in the camera head just in front of the CCDs. One cm of tungsten surrounds the CCDs in the camera head for radiation shielding. The camera head is thermally isolated from the optics structure with fiberglass standoffs, and it is maintained at -70˚C. This is accomplished by routing a heat pipe to a 0.25 m^2 radiator located directly above it, which has a direct view of space. This low temperature ensures negligible dark current over the short integration periods and minimal degradation from radiation effects. Actively controlled resistive heaters are also included on the focal plane for extra regulation to ±10 mK. A quartz window forms a vacuum seal on the front of the CCD camera head to prevent contaminants from condensing on the cold detectors. The focal plane can also be heated to remove contaminants and anneal radiation damage.

❏ *Instrument Electronics and Processor:* The functions of the instrument electronics are shown in Foldout 2, Figure FO 2-7. A precision oscillator drives the clock driver electronics, which precisely shift charges between the columns and rows of the CCDs. A 48 channel preamp amplifies the CCD output signal chains and digitizes the data. The instrument processor accepts this digitized data, extracts pixels containing stars, adds a time stamp, and passes these pixels on to the S/C. It also maintains the CCD clocking rate so that it is synchronized with the S/C rotation.

The CCD clocking and preamp electronics are housed in separate boxes (25 x 15 x 30 cm) located below the camera head and behind the primary mirror. The preamp provides three separate pre-selectable parallel gain stages and 12 bit low-power ADCs. An FPGA assembles the digital output word (12 data bits plus 2 gain bits), that is output for each channel. Heat (30 W) is conducted from the preamp to heat the primary mirror and its mount structure.

The instrument's processor consists of mass storage, interface, and processing components. A catalog of 4 x 10^7 stellar positions and fluxes is stored before launch in a 3.2 Gbit solid-state recorder. Input star catalog positions will be updated from the ground on a monthly basis. Targets of opportunity can be added, and stored values can be updated during the mission. Table 2-2 lists the primary instrument processor functions.

Table 2-2. Instrument Processor Functions

• Basic instrument housekeeping.
• Establish the instrument attitude.
• Accept the incoming digitized data from each CCD channel and extract the pixels that contain desired stellar observations.
• Time stamp the extracted information and pass it to the S/C for storage and transmission to the ground.
• Monitor and adjust the CCD column clocking frequency to maintain time-delayed integration.

❏ *Instrument Processor Operations:* Initial operation is established as follows. Instrument attitude and rotation rate are coarsely established with star trackers, which are mounted on the optical bench. Fine attitude and rotation values are then determined from the sub-pixel centroids of bright stars (see Section 2.3.1). Once the attitude and rotation are determined to be within adequate bounds, the major mapping mode can begin.

In the major mapping mode, digital pixel data are sent from the preamp to the processor via fiber optic links. These incoming data are windowed by the processor's FPGAs; they extract 5 (in-scan) x 3 (binned cross-scan) pixels centered at the position expected for each star from star catalog values. The FPGAs also time stamp the pixel data for future astrometric processing. Each FPGA processes two channels of information, requiring a total of 24 FPGAs. The instrument computer's central processor is a fault-tolerant PowerPC flight system (General Dynamics Information Systems) that provides up to 480 MIPS performance and low power consumption. This processor receives the extracted pixel and time stamp information from the windowing FPGAs, which share its VME bus. The processor packages and sends these data to the S/C over an IEEE 1553 bus. The processor also monitors the timing of the TDI and adjusts the CCD vertical clock frequency so that the CCD readout is synchronized with the S/C rotation to better than 0.05 pixel over a single CCD. A single R3000 CPU computes the centroids of selected bright stars that traverse the CCDs both above and below the focal plane's central obscuration to determine the rotation rate. The CCD vertical clocking frequency can be updated as often as once per minute, but we anticipate doing so far less often.

Table 2-3. Instrument Properties

Item	Mass (kg)	Power (W)
Mirrors	54	—
Optical Bench	14	—
Strong Backs	24	—
Other Structure Components	15	—
Baffles, Mounts, & Fasteners	10	—
CCD Camera Head	14	—
CCD Electronics & Mount	15	70
Thermal Hardware & Shields	10	• 150 (peak) • 120 (mean)
Instrument Processor	9	• 30
TOTAL	165	• 250 (peak) • 220 (mean)

2.2 Mission.

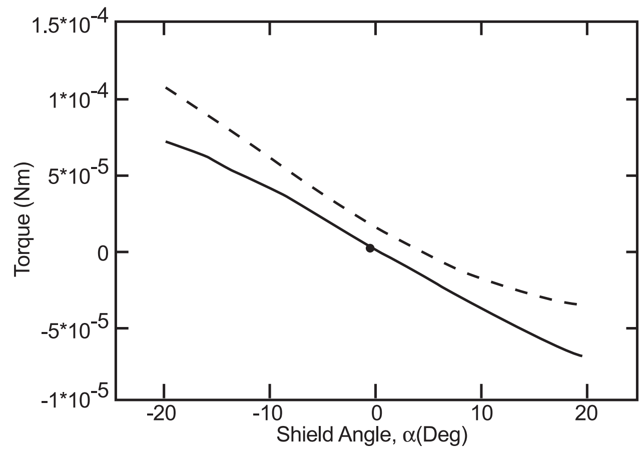
2.2.1 Observing Strategy. After mapping begins, the S/C completes one revolution every 20 minutes, and it uses solar radiation pressure to smoothly precess the spin vector around the sun line once in 10 days. The two FOVs sweep out successively overlapping "observing spirals." Thus, the entire sky is observed from different angles during the mission. As the S/C spins, star light enters both FOVs and crosses the CCD array in a TDI mode. As an image nears the CCD edge, surrounding pixel data are binned (cross-scan direction), time-stamped, and extracted. The on-board star catalog, knowledge of the attitude, and rotation rate are used in this process. Data are downlinked to the ground, where processing continues.

2.2.2 Solar Radiation Precession. An innovative aspect of this mission is the use of what is typically a disturbance torque to drive the required S/C precession. The sun shield serves as a solar sail to produce a torque that moves the spin axis (more precisely, the angular momentum vector) around the sun line. Because FAME is a stable spinner and it is passively damped by liquid propellant, the motion is stable and can be sustained indefinitely.

While solar sails often provide mission-critical torque balances (Washwell 1996), this is the first proposed use of solar torque to drive S/C attitude changes. For an ideal sun shade (i.e., a conic surface with uniform reflective properties), and given the vehicle mass properties and spin rate, the shield's sweep angle can be trimmed so that the solar torque yields the desired rate. Calculations show that, even for small angles, there is adequate control authority without the need for high precision adjustment (Figure 2-3). Gravity-gradient torques, spin-axis offset, and spin-axis misalignments also contribute to variations in spin and rates. Each of these disturbances can be rendered small through proper placement of solar cells, surface material selection, component placement, and spin balancing before launch. Preliminary analysis shows that spin axis misalignment must be ≤ 0.045 deg, and that inertia ratio (I_t/I_s) must be between 0.9 and 0.67. Both requirements are met using proposed ISV dimensions.

Solar Precession Models: Simulations show the solar torque precession approach to be robust to variations in ISV's mass properties and sunshade optical properties (see Figure 2-3) where the sun shade is modeled in four equal segments each swept back by 2.6 deg. Sun shade optical properties are consistent with a highly reflective surface on one pair and partial coverage by solar cells on the other pair. The effect of gravity is included, and the inertia ratio is 0.83. Foldout 2, Figures FO-5 and FO-6 show that the spin axis precesses about the sun line though for this sweep angle it does not complete a full 1.5 cycles in 15 days, and it is starting to fall behind the motion of the Sun. Nevertheless, more than 1,080 spin cycles were completed without a single thruster firing. If the aspect angle continues to drift the RCS will be used to return it to 45°. Additional studies are proposed in Phase A.

2.2.3 Orbit. Section 4.2 provides a discussion of the orbit selection and related information.



Torque around 2 points along the cylindrical axis of S/C (front, solid; 2m back, dashed) vs. shield angle, deg.

Figure 2-3. Solar Precession Torque (N-m)

2.3 Data Analysis and Archiving. Although FAME will observe 400 times as many stars, 20 times more precisely than the successful *Hipparcos*, the two missions share many similarities. Both use a precessing, spinning satellite with two FOVs to determine astrometric parameters for stars distributed globally. Both have one, high-quality, coordinate measure, and a much less precise orthogonal one. The FAME astrometric data reduction method benefits from *Hipparcos* heritage (Perryman et al. 1989; Kovalevsky et al. 1992; Lindegren et al. 1992; ESA 1997), but, from a data analysis perspective, FAME improves on *Hipparcos* in two ways.

❏ First, FAME spins and precesses smoothly, whereas *Hipparcos* used frequent ACS jet firings to precess the S/C. As a result, FAME has long periods of coherent rotation; there is no need to break the rotation into small segments and to estimate the rotation parameters of each segment.

❑ Second, FAME uses CCD detectors that have high quantum efficiency, are distributed over a wide FOV, and simultaneously integrate signals from many stars. The first two considerations increase the instrument's information rate, and the third increases the *rigidity,* or how well one can measure the separation of two widely spaced objects.

2.3.1 Astrometric Reduction Pipeline. The astrometric data reduction and analysis (Foldout 2, Figure FO 2-8) has six major steps.

❑ *First-Look and Troubleshooting:* Data gathered from the FAME satellite must be checked immediately after downlink. Image detection, image quality, and satellite attitude are to be continuously monitored. Any anomalies in the data will trigger an anomaly recovery activity. One should note that the FAME control center and the first-look data analysis will both be located at the USNO, so there will be continuous contact between the groups.

❑ *Centroiding:* All pixel data surrounding each star will be telemetered to the ground, along with CCD column numbers and row-shift epochs. Events are archived both before and after calibration. Calibration entails correction for known CCD problems. The calibrated pixel data are then used to fit the parameters of a target model. This model includes the location in both the scan and cross-scan directions of the centroid, the amplitude of the signal, and at least one aspect of the shape of the diffraction-limited image. Initially, a simple stellar model will be used. In later iterations, the photometric data will be available for selecting and fitting a more suitable model of the shape of the image. An indication of image complexity, such as an extended object or multiple star system, is made at this time.

❑ *Observing-Spiral Reductions:* As FAME rotates and precesses, the CCDs map out a spiral band, or observing spiral, on the sky. The prime tasks in the observing-spiral reductions will be to characterize the satellite's motion and investigate changes in the optical path during an observing spiral. Once these are computed, using an (arbitrary) origin and the timing data, coordinates can be determined for all stars along the observing-spiral.

Knowledge of the S/C's angular velocity, $\omega(t)$, is critical since the separations (and therefore relative positions) of stars are determined by $\omega(t)$ and transit times of the centroided images. A Fourier expansion of $\omega(t)$ will be integrated over the time for a star to cross both FOVs. The Fourier coefficients are obtained by equating such integration to the basic angle. Using these two view directions (separated by the basic angle) in this way imposes many closure conditions on $\omega(t)$ and avoids the scenario of $\omega(t)$ containing increasing errors stemming from a "random walk." This use of the two FOVs is taken directly from the *Hipparcos* design. Simulations show that for FAME the stability of the basic angle and CCDs will contribute little to the error budget. Any such instabilities will, however, be monitored using the observations.

The time varying axis of rotation needs to be determined to precision of 100 μas to minimize projection effects due to unknown field rotation. Accuracies at this level must be determined from the stellar data from the CCD array. The combination of transit times, location of transit images in the cross-scan direction, and a priori positions of those stars will yield the plane of rotation, $xy(t)$, and axis of rotation, $z(t)$. The instrumental model developed for each spiral during this stage will be archived.

The abscissa, or one-dimensional angular separation in the along-scan direction, of each star can now be calculated and archived. (Note that information in the ordinate, or cross-scan direction, is an order of magnitude less precise and, in practice, will probably not be used at this step.) The abscissa is the integral of $\omega(t)$ between the transit time of an arbitrary origin, and the transit time of the star. The establishment of an origin for each observing-spiral will be achieved by using a subset of stars whose positions are known a priori to 20 mas from *Hipparcos* data. This origin, however, will contain a small rotation due to scatter in the *Hipparcos* data. This rotation will be removed in the sphere reconstruction stage.

❑ *Sphere Reconstruction:* Each observing-spiral defines an independent system. In the sphere reconstruction step, these systems are all brought together to form a single, global system, removing all arbitrary rotations. This will be achieved by solving for the origins as well as the astrometric parameters of a subset of stars using, primarily, the abscissae from the observing-spiral reductions spanning the entire program. Only point-like stars with constant space-velocities are used.

The observed abscissae from this subset are modeled as random variables that are expressed as a function of astrometric parameters (position, proper motion, and parallax), observing-spiral origins and orientations, and global parameters. The global parameters are a combination of periodic basic-angle variations, corrections due to gravitational light deflection, corrections due to aberration, and others. A system of unit-weight observation equations can be formed from the data. The astrometric parameters are adjusted for each star being used in this step, then eliminated from the equations as if the values for the observing-spiral origins and global parameters are correct. The entire process is iterated until corrections to the origins and global parameters converge. We are left with a description of the satellite behavior and a computation of a rigidly defined origin for each of the observing-spirals. New values for all abscissae and ordinates are recomputed and archived.

At first glance this step appears computationally problematic. However, one must note two things. First, only a subset of the stars will be used at this step. We envision fewer than 100,000 stars will be required, possibly much less depending on the stability of the optical system and satellite rotation dynamics. Second, the matrix containing the observables is sparse, and thus we will apply suitable hyper-structuring to reduce the original matrix to smaller submatrices that can be inverted individually and later recombined (de Vegt & Ebner 1974).

❑ *Astrometric Parameter Determination:* The new abscissae and ordinates computed in the sphere reconstruction stage are used to make a weighted, least-squares fit (one fit per object) to all stars to yield the five astrometric parameters. For each star there will typically be about 4000 observations. Residuals will be examined for signs of nonlinear proper motion, which would indicate the presence of a nearby gravitating body. Under these circumstances, additional parameters will be determined. Investigations regarding previously undetected instrumental biases like systematics dependent on CCD, color, and magnitude will be performed.

❑ *Iterations and Global Alignment:* The data analysis is, by necessity, an iterative process since some instrumental characteristics can only be determined post-launch. For example, due to the large number of observations to be processed and the good observational diversity, numerous parameters can be estimated for each of the CCD chips. These might include coefficients of a cyclic bias model, displacements from nominal positions, and even a polynomial describing astrometric shifts as a function of cross-scan position within each chip. As the instrument becomes better understood, we will be able to address these models in more detail.

We will re-centroid each observation using improved instrument models and the photometric reductions. Additionally, we will use updated positions from the initial reductions where a priori information is used, such as in determination of the axis of rotation. It is expected that less than three iterations will be required before convergence.

The global system defined by FAME will be internally more precise and rigid than any existing reference frame. However, due to the observing strategy, it can contain a global rotation. Therefore, the entire system will need to be aligned with another established frame. This will be done by rotating the FAME frame to coincide with the International Celestial Reference System (ICRS) within the errors of the ICRS. This is analogous to the recent alignment of *Hipparcos* to the axes of the ICRS.

2.3.2 Photometric Pipeline. This pipeline consists of (1) identification of sources, (2) photometric calibration, and (3) iteration and cataloging.

❑ *Identification of Sources:* All stars crossing the photometric detectors will be identified with the on-ground input catalog that contains photometric and astrometric information. Knowledge of the instantaneous pointing, an up-to-date catalog, and the detector readouts are sufficient to unambiguously identify unconfused stars, i.e., stars that are well isolated from other stars on the sky. Calibration stars are identified as they are encountered.

❑ *Photometric Calibration.* Photometry of the calibration sources will be used to correct for sensitivity drifts in each band. A photometric model of the calibration stars and instrument sensitivity will be derived from the observations, yielding a set of stellar fluxes and a time-varying detector response. With a calibration source observed every few seconds, linear drifts better than 10^{-6} per second will be calibrated, yielding a photometric calibration good to 1 milli-magnitude. Templates will be derived from optical modeling of the PSF on the scanned detector and validated using calibration star observations. These templates will be fit to all detected stars to determine their fluxes.

Iteration and Cataloging: A global photometric calibration will be performed, taking into account the detector performances and all stellar flux measurements with sufficient signal-to-noise. Stars with the highest variances (and hence likely intrinsically variable) are iteratively removed from the calibration at each step. This calibration will be kept in the photometric archive, thereby giving the best photometry available at any given time. Inevitably, some calibrators will have intrinsic variations giving large residuals in the photometric models. The star with the largest residuals can be dropped and the analysis redone. The remaining calibrators are the most stable, and give the best photometric calibration. At the end of the mission, data from the archive will be combined to form the photometric catalog, including a light-curve database of the variable stars.

2.3.3 Data Validation Plan. Many different investigations can be undertaken to ensure that the data are being acquired and processed correctly. We will determine whether centroided pixel data fits the expected RMS error, whether the S/C rotational data fits a reasonable model of rotation, and the changes in the rotational parameters using different subsets of stars. We will analyze the data to ensure that subsets of observing-spirals give the same results, within the errors, as the complete ensemble of observing-spirals. We will ensure that the residuals are small and non-symmetric with respect to CCD phase, star color, and S/C rotation (with respect to the Sun and Earth). Although the FAME astrometric parameters will be the most accurate available, stars observed with both *Hipparcos* and the Navy Prototype Optical Interferometer (NPOI) will have position and proper motion accuracies of 1 mas and 100 μas/yr, respectively, thereby providing an independent check of four of the five astrometric parameters for a few thousand brighter stars.

2.3.4 Data Archiving. Although the S/C produces on the order of 30 Tbits (4.0 T bytes) of data over the lifetime of the mission, currently available databases can manage this volume. There are seven stations in the analysis system at which the data or analysis results are archived and may be distributed to the public. These are: (1) the pixel data archive, to contain the raw data from the satellite; (2) the centroid archive, to include time, location, and amplitude of transit events; (3) the instrumental model archive, to comprise the description of the satellite motion and characteristics of the optical path; (4) the spiral archive, to include the positional data from each observation; (5) the photometric archive, to hold data from the photometric pipeline; (6) the astrometric parameter archive, to include positions, motions, and parallaxes following their determination; and (7) the final catalog archive, to encompass the results of the astrometric and photometric pipelines, project description, hardware details, and reduction methodologies.

The PI is responsible for all data deliveries. The specific products to be delivered to NASA's Astronomical Data Center will be all of the seven archives. These data will be available within 1 year after the satellite data acquisition is completed, to allow for the data analysis and verification processes to be completed. It will be possible to make available an interim solution containing only positional and photometric data (not proper motions or parallaxes) about 18 months after launch. However, the experience of the *Hipparcos* consortia demonstrated that it is not advisable to provide less than full-accuracy astrometric data since many systematic effects can still be present, thus leading to spurious scientific conclusions.

2.4 Science Team. FAME's worldclass science team (Table 2-4) consists of scientists whose roles and expertise allow the mission to accomplish all of its objectives. The team will publish scientific findings from the mission and communicate these findings to the public. FAME's scientists are well-versed in precise astrometry (deVegt, Gatewood, Johnston, Seidelmann, Röser and van Altena), instrumentation (Shao, York, and Phillips), analysis (Reasenberg, Urban), astrophysics and distance scales (Huchra, Sandage), dark matter (Gould, Bahcall), photometry (Van Buren), stellar evolution and luminosity (Greene, Monet), low mass companions and exoplanets (Latham, Shapiro), and astronomical catalogs (Lasker, Urban).

Table 2-4. FAME Science Team

Name	Role & Responsibility	Commitment (%)	
		Phase B/C/D	MO&DA
Dr. Bahcall; Princeton	CoI; Application of astrometric results to astrophysics	1	5
Dr. deVegt; Hamburger Sternwarte	Hamburg Sternwarte; CoI, Astrometric accuracy and error sources	1	5
Dr. Gatewood; Univ. of Pittsburg	CoI, Parallax Investigations	1	10
Dr. Gould; Ohio State Univ	CoI; Galactic Structure, mass density and profile of the disk	1	10
Dr. Greene; LMMS	CoI; Stellar evolution	75	50
Dr. Horner; USNO	CoI; Exoplanets, stellar structure, and stellar activity	100	100
Dr. Huchra; SAO	CoI; Cosmological distance scale	1	5
Dr. Jefferys; Univ. of Texas	CoI; Statistical modeling, data processing	20	25
Dr. Johnston; USNO	PI, Celestial reference system/frame (astrometric grid)	50	50
Dr. Lasker; STScI	CoI; Cataloging, comparison to surveys	1	5
Dr. Latham; SAO	CoI; Low-mass companions, exoplanets	1	10
Dr. Monet; USNO	CoI; Luminosity function of nearby stars	10	20
Dr. Phillips; SAO	CoI; Complex targets, low-mass companions, exoplanets, instrumentation	100	100
Dr. Reasenberg; SAO	Science team Deputy Chair; Complex targets, low-mass companions, exoplanets, analysis	100	100
Dr. Röser; Astronomisches Rechen-Institut	CoI; DIVA collaboration	1	10
Dr. Sandage; Carnegie Observatory	CoI; Distance scales	1	10
Dr. Seidelmann; USNO	Science Team Chair; Astrometry, non-singular stars	75	75
Dr. Shao; JPL	CoI; SIM collaboration, instrumentation	1	5
Dr. Shapiro; SAO	CoI; Complex targets, low-mass companions, exoplanets	1	5
Mr. Urban; USNO	CoI, Astrometry, catalogs, double stars, analysis	100	100
Dr. van Altena; Yale	CoI; Stellar dynamics, instrumentation	1	20
Dr. Van Buren: IPAC	COI: Photometry, multiwavelength	75	75
Dr. York; Univ. of Chicago	CoI; Sloan Digital Sky Survey collaboration	1	5

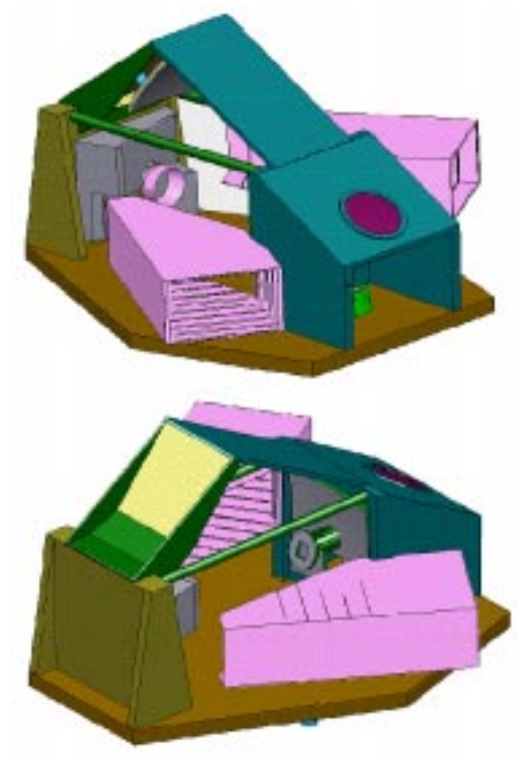


Figure FO 2-1. FAME Instrument

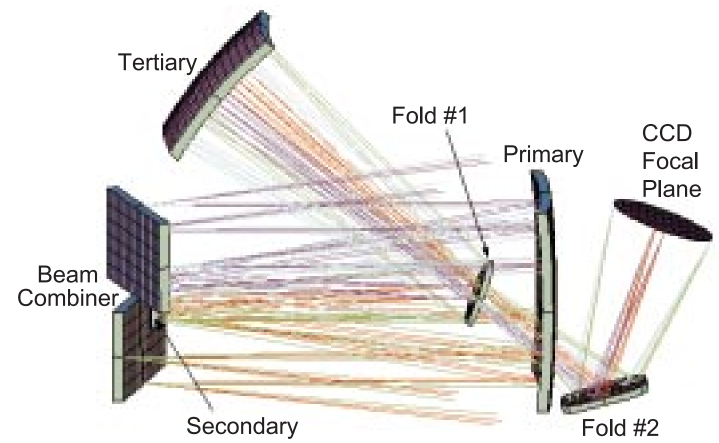
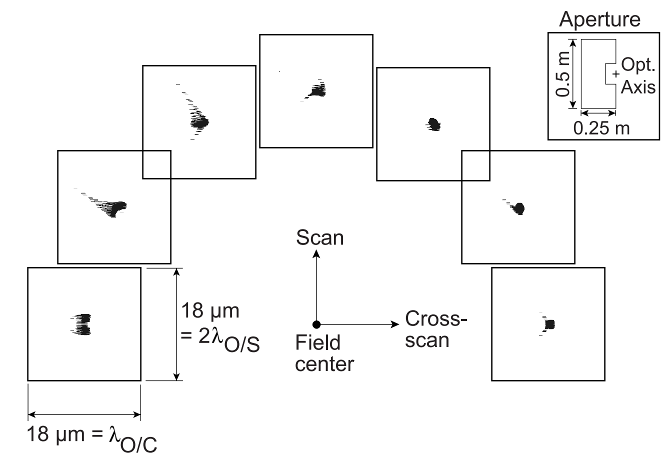


Figure FO 2-2. FAME Optical Raytrace



Rms spot size along this arc is 0.8 micron, matching the rms over the whole field. There is bilateral symmetry in the scan direction. Manufacturing and alignment errors are not considered. This diagram indicates the distortion due to the optical design, not the resulting point spread function.

Figure FO 2-3. Spot diagram for points along an arc at a field angle 1.03˚ from the center

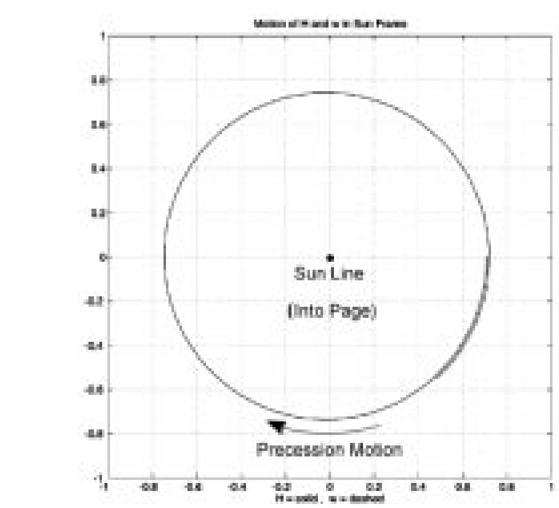


Figure FO 2-5. Spin Axis Precession

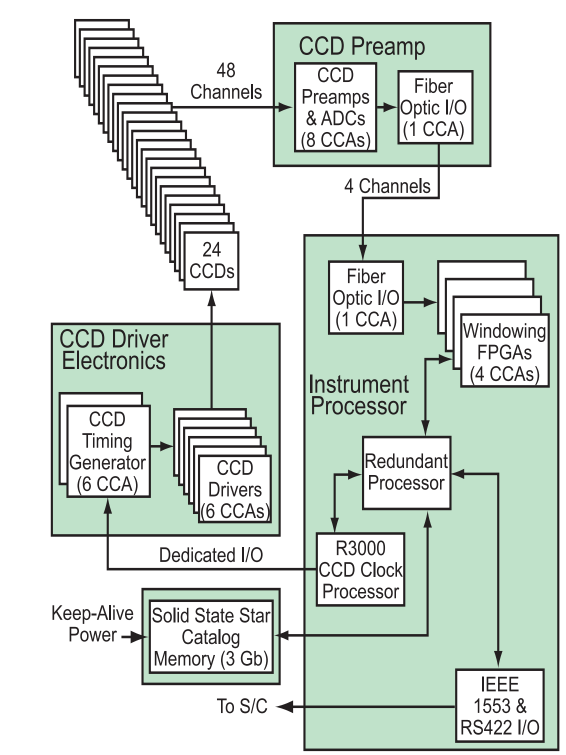


Figure FO 2-7. Electronics Block Diagram

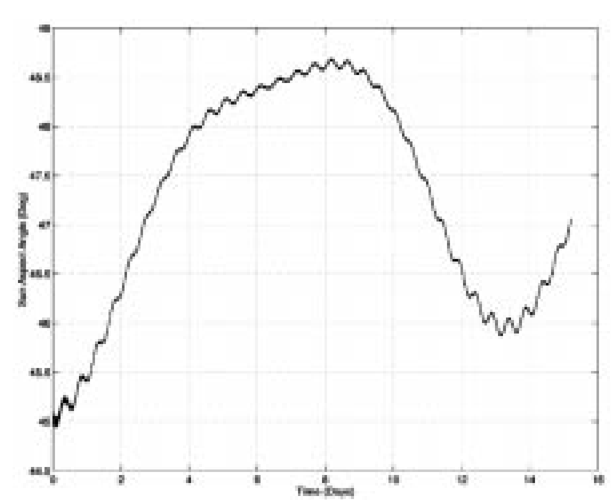


Figure FO 2-6. Sun Aspect Angle Variation

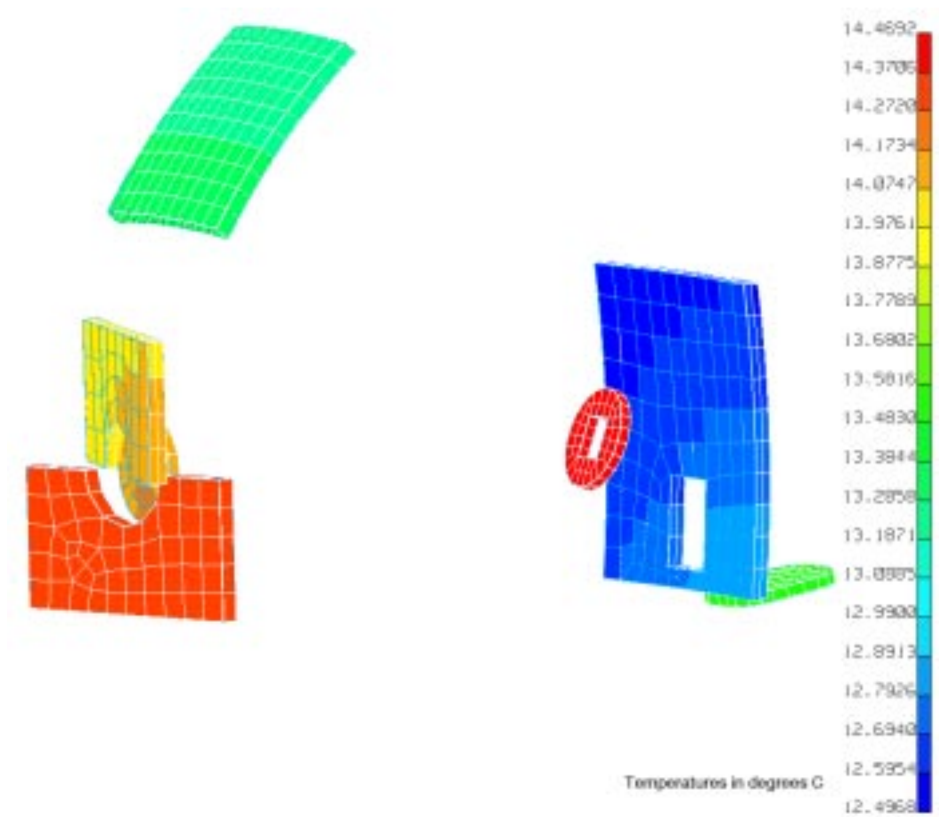


Figure FO 2-4. Optics Surfaces Thermal Maps

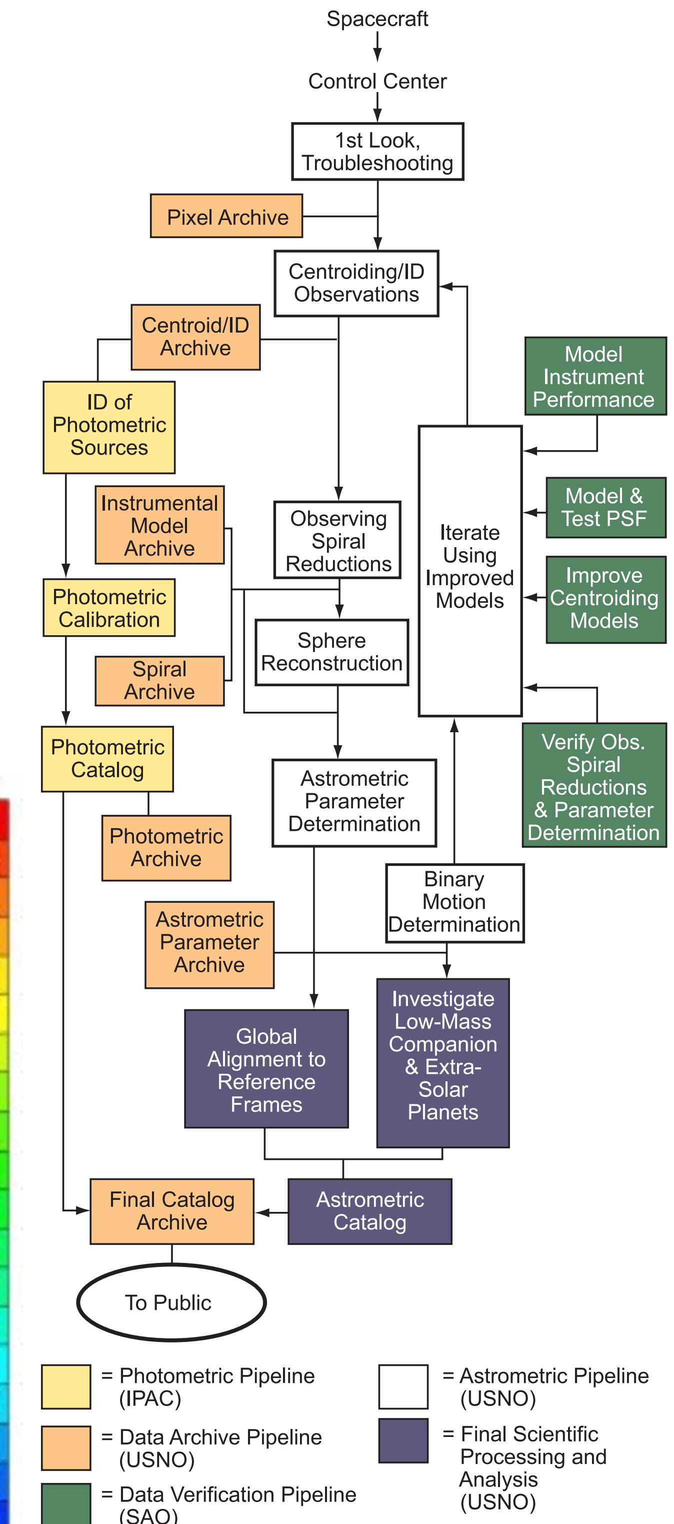


Figure FO 2-8. Data Analysis and Archival

3. Education, Outreach, New Technology, and Small Disadvantaged Business Plan

3.1 Education and Outreach. FAME provides an exceptional opportunity for education and public outreach because many of the concepts are easily understandable by non-scientists, including school-aged children. Astrometry is a highly geometric subject with an exceptionally long history; significant work was done by the Greeks. The FAME education effort would naturally include basic ideas about angles and angle measurement (from the schoolroom protractor to spaceborne telescopes), Earth's orbit (and radar techniques for measuring the inner solar system), parallax and the idea of determining the distance to a place without visiting it, motion of stars (which contradicts popular belief), and the universality of dynamic systems dominated by gravity. Classroom experiments can include both "discovering" stellar companions by plotting data (pre-fit residuals) and measuring distances of a few meters to a few hundred meters by parallax. In an advanced project, students in pairs of well separated schools would determine the distance to the Moon by coordinated measurements of the angle between the Moon and a bright star. Some may relate this to the work of the Greek astronomer, Hipparchus (Ca. 150 BC).

It is important that the public understands the limitations in current scientific knowledge, and how these limitations affect many branches of astronomy. We will address how the FAME mission will push back these limitations by adding to our understanding of the size, age, and structure of astronomical systems, including the universe itself.

Our Education and Outreach plan will build upon CfA Science Education Department (SED) successes in developing effective programs to educate non-scientists in astronomy and space science and to correct prevalent misconceptions in these fields. Our results to date include video documentaries (Schneps & Sadler, 1988), astronomical teaching materials (Coyle et al., 1992), and institutes for teachers (Ball, Coyle, & Shapiro). These products changed the teaching of science—particularly astronomy—nationally.

We will first identify commonly held scientific beliefs pertaining to FAME's science, including concepts of the size and distance scale of the universe and available measurement techniques. After an initial search of the educational literature, we will interview both school-age children and adults to determine how prevalent these scientific beliefs are among the general population. From these interviews, we will develop assessment instruments to measure changes in the understanding of those exposed to our educational and outreach activities. NRC Standards list a cohesive set of science concepts to be learned from grades K-12. A subset directly relates to our project. We will produce three modules to help teach these ideas: grades 4-6, grade 7-9 earth science, and high school physics. Techniques will include hands-on activities, cooperative learning activities, and engineering challenges. From our group of project scientists and SED educators we will build a team to implement our Education and Outreach plan. We will also draw upon a very rich resource, the wide range of exemplary science teachers who have participated in our institutes and workshops. At summer workshops, selected teachers will create materials which will then be tested on their students during the school year. These teachers will present the final materials at National Science Teachers Association conferences as program items (total annual attendance is approximately 22,000), and at meetings of both the Astronomical Society of the Pacific, and the American Association of Physics Teachers.

In coordination with the Boston Museum of Science Charles Hayden Planetarium, we will develop a planetarium program exploring stellar distance measurement that can be replicated at other major planetariums. Loch Ness Productions will aid in developing a program for smaller planetariums. The Astronomical Society of the Pacific will distribute a slide set developed for this planetarium show that documents the FAME project. A "traveling kit" of materials, similar to those produced for lending at the Children's Museum of Boston, will be designed and tested so that interested scientists will have ready-made aids for classroom visitations. These kits will be replicated and made available to scientists and staff at all FAME sites.

On a more personal scale, the USNO conducts public tours weekly. These tours attract more than 4,000 people each year from all age, ethnic, and economic groups. Discussions, demonstrations, and informational handouts will inform visitors about the current knowledge of astronomy and how FAME will expand that knowledge. Also, we will better foster interaction with the local elementary schools. During the experiment, students from the Washington DC area in grades four through six will apply FAME data in a research project. This age level is targeted because the choice of careers in math and science frequently occurs in these grades. Further, the schools in the Washington DC area contain a large majority of minority and disadvantaged students who are under the 50 percentile in science scores. This program will demonstrate to these underserved students the results of applying math to raw data, and how facts support or change scientific theories. A database will be established to allow students to reduce data and study stars and planets. Students will visit with USNO scientists and interact with them in the classroom via a Connectix camera and CU-See Me software. Scientists will discuss student research projects and suggest further enhancements to their investigations. Students will interpret their results to determine which of the observed stars are double stars that may have massive planets.

3.2 Media Relations. The USNO Public Affairs Office is experienced in interacting with the news media. Members have appeared often on local (Washington, DC) and national television and radio. This office will coordinate media relations with the public affairs offices of other institutions and corporations participating in FAME. The USNO Public Affairs Office will issue national press releases and will coordinate issuing local press releases in Boston and the San Francisco Bay Area, highlighting the local participation of Smithsonian Astrophysical Observatory (SAO) and Lockheed Martin. The USNO Public Affairs Office will also publish press releases on the USNO web site as well as maintain a press release page on the FAME web site. Press conferences will be held for major announcements, and a press conference will be conducted in association with the FAME launch. Appropriate NASA officials will be invited to participate in all press conferences. We will seek to build on the activities and plans of other NASA education initiatives, including NASA Education Forums (the most applicable of which is located at SAO). The materials and programs developed by our group will greatly enhance public understanding of astronomy.

3.3 New Technology. FAME takes a conservative approach and is using only proven technologies for the S/C and instrument to reduce overall program risk. However, the investigation is using an existing technology application in an innovative manner to enhance total mission data collection. Specifically, the use of solar radiation pressure for S/C precession, while not strictly a new technology, is an innovative use of existing solar sail technology (Washwell 1996). Solar radiation pressure enables a fast rotation rate that favors use of a short focal length telescope, reducing instrument complexity and cost. While the use of a short focal length telescope for the FAME mission poses some technical risks, it offers a substantial payoff in terms of the science mission. During Phase A these technology areas will be studied thoroughly. If the risk is deemed to be high, the mission can be reconfigured for a longer focal length telescope, and to use thrusters for S/C precession.

3.4 Small Disadvantaged Business Plan. The FAME team is committed to exceeding NASA's goal of 8% established for Small and Small, Disadvantaged Business (SB/SDB) subcontracting. The details of the SB/SDB plan will be finalized during the Phase A study and submitted in a formal deliverable. During Phase B, we will work with USNO's Business Office to identify and maintain additional contracting options that meet these goals.

❏ USNO has an aggressive program designed and implemented to use SB/SDB in subcontracting and procurement actions. Over 25% of USNO contracts in FY97 were awarded to SB/SDB, which included women-owned businesses, historically black colleges and universities, and minority institutions. As a primary management goal for the investigation an assigned USNO Business Manager will administer the SB/SDB program, and the PI will approve it. Both are jointly responsible to assess and supervise the acquisition program and to establish SB/SDB subcontracting goals that satisfy NASA guidelines. Starting in Phase B, and continuing throughout the mission, detailed records will be maintained associated with the SB/SDB Subcontracting Plan (Table 3-1).

Table 3-1. SD/SDB Subcontracting Records

• Documentation of USNO and key subcontractor SB/SDB outreach activities, including participation in SB/SDB programs, and source search activity.
• Documentation of industrial contracts and their subcontracts for awards in excess of $100,000, indicating whether or not SB/SDB concerns were solicited and the reason for the award not being made to a SB/SDB.
• Documentation of acquisitions and demonstration of compliance with SB/SDB procedures and performance.
• Documentation of workshops, guidance, and training given acquisition personnel regarding SB/SDB use.

❑ NRL, our major governmental participant, sets goals for awarding contracts to Women-owned businesses, SB/SDBs, and Historically Black Colleges and Universities. Table 3-2 compares NRL's FY97 goals and achievements. Although some of these categories overlap, the results clearly exceed NASA's 8% target goal.

❑ LMMS, our major industry participant, has an outstanding record meeting SB/SDB goals. For example, LMMS won the 1996 Defense Logistics Agency and Small Business Administration "Outstanding Program Award". In 1996, LMMS awarded 15% of its subcontracts under NASA prime contracts to SDBs. LMMS was recently named "Corporation of the Year" by the Industry Council for Small Business Development.

Table 3-2. NRL's SD/SDB Goals

% of Contracts Awarded	Goal (%)	Achieved (%)
Women-owned business	3.4	5.3
SB/SDB (minority-owned)	7.5	7.9
Historically Black Colleges, Universities, and Institutions	5.0	4.2

4. Mission Implementation

FAME mission elements are provided by: (a) USNO, responsible for program oversight, mission integration, mission science, data analysis, and data archiving; (b) LMMS, responsible for designing and building the FAME instrument; (c) NRL, responsible for program management, developing the spacecraft (S/C) bus, flight system integration (payload and launch vehicle) and operating the back-up mission ground site; and (d) Omitron, Inc., responsible for building and operating the primary mission ground site. The integrated space vehicle (ISV) undergoes system level integration and test at NRL's payload checkout facilities. The ISV is launched aboard a Delta 7425. After launch, the mission is controlled from USNO in Washington, DC via the COTS ground station provided by Omitron, Inc. NRL's Blossom Point MD ground station provides alternate command and control.

4.1 Mission Design. FAME's baseline approach is simple, yet powerful. A single observing mode, involving no moving parts, collects all science data. A geosynchronous orbit (GEO) was selected due to low gravitational and magnetic torques, and a near continuous downlink capability. Cost-effective fixed solar arrays support all operations, and the ISV's thermal design allows it to survive indefinitely, even in the stowed configuration.

4.1.1 Collecting, Processing, and Storing Data. The FAME instrument acquires, processes, and downlinks data continuously. Downlinking is suspended occasionally to support antenna switching (~msecs) and ranging (~mins). The on-board recorder stores data during these outages, and serves as a rate buffer when data rates exceed nominal values (i.e. when imaging the galactic disk).

4.2 Orbit Selection. FAME is launched into a nearly circular orbit (Foldout 4, Table FO 4-2) at geosynchronous altitude with a 28.7 deg inclination (Foldout 4, Figure FO 4-2). The longitude of the ascending node (LAAN) is selected so that FAME is always in view of USNO's ground station. E-W stationkeeping operations are performed several times during the mission and no N-S stationkeeping is required. The right ascension of the ascending node (RAAN) is selected to minimize eclipse periods. Nominally, the ISV experiences a pair of 4-5 weeks eclipse windows each year, with a maximum eclipse period of 70 minutes. There are no other instrument-derived launch constraints. The ISV is de-orbited at the end of the mission by raising it to a super-synchronous orbit.

4.2.1 Telecommunications. An S-Band transponder, CCSDS protocols, onboard omni-directional antennas, and a COTS downlink ground site at USNO provide near-continuous 24-hour downlinking, command, and control. A Navy-owned-and-operated facility at Blossom Point MD provides alternate command and control. Our system can connect with the NASA Communications (NASCOM) network for support during launch and/or anomalous operations, similar to the method used by *Clementine's* operations center. Foldout 4, Figure FO 4-1 shows the planned telecommunications architecture.

4.2.2 Flight Operations. Activities include initial acquisition, orbit transfers and maintenance, normal science data collection, and S/C calibrations. During initial acquisition and orbit transfer, the UCC, NRL's Blossom Point, and supporting NASA ground stations maintain near-continuous contact. Special maneuvers are not required for S/C or instrument calibration; however, sunshield adjustments are required to trim out solar torques. These adjustments consist of changing the shield sweep angle and then monitoring the vehicle motion.

4.2.3 Margins. Foldout 4, Table FO 4-1 summarizes margins using NASA's guidelines.

4.3 Instrument Accommodations. Instrument details are covered in Section 2. This section contains specific S/C accommodation parameters.

4.3.1 Error Budgets and Pointing. FAME's astrometric accuracy is shown in Foldout 1 Table FO 1-3. The systematic error budget is shown in Foldout 4, Table FO 4-5. Table 4-1 shows the required pointing during science observations. Error sources are divided into four parts: stochastic, internal systematic (errors due to the instrument), external systematic (errors that would affect an ideal instrument measuring at the same point in space), and intrinsic (e.g., motion due to resolved companions). Many of the internal errors vary systematically with parameters such as field position and position within the CCD chip. These errors will be well-studied, with about 1.8×10^{11} observations in total, 1.1×10^{10} per chip, and 5.3×10^{6} per CCD column. Each star is observed 270 times by each chip.

Even if it were necessary to include in the model one or more parameters per CCD column, there are sufficient data to support the estimation. Laboratory characterization determines the nature of the CCD-induced errors and support parametric CCD models. Refined values are determined from on orbit data.

❑ Numerical experiments were used to evaluate FAME's centroiding precision (Phillips & Reasenberg 1998). For V=9 the precision is 530 μas, and for V=12.3 it is 2400 μas. This corresponds to 1/460 of the half-width at null for the V=9 case and 1/100 for the V=12.3 case.

In the laboratory and using stare mode, centroiding was demonstrated to comparable precision: 1/1200 of the half-width at null with a circular aperture (Winter 1998). The uncertainties as a fraction of a pixel are 1/770 for FAME (V=9) and 1/500 with laboratory work. FAME uses TDI, which averages some types of error, but CCD read noise raises the variance by a factor of two for the faintest stars.

❑ An undetected orbiting (stellar) companion will bias the estimates of position and proper motion, and to a lesser extent, parallax. For systems with separation of the components greater than ~250 μas, modeling of the Point Spread Function (PSF) will detect the companion, and positions will be estimated separately for both. The width of the image, i.e., effective temperature, can be estimated for a V=9 star to within 1% in a single measurement (Phillips & Reasenberg 1998). To detect a companion to an object, we use all estimates for the image width of that object over the entire mission. Orbits with period less than twice the mission duration will also be detected in the position residuals. The shift of the center of light, for a system with the maximum undetected separation, is ~1/4 of the separation or 60 μas, and occurs when the magnitude difference is ~2.9. Systems with separation and magnitude such that they escape detection, yet a large enough shift of the center of light to be a significant error source, will be treated specially.

❑ The astrometric accuracy can be substantially improved in the 5-8th magnitude range by any of a number of innovative techniques. Anti-blooming techniques may make it possible to precisely measure the wings of the PSF to obtain the star's position. This technique is currently under development by USNO. Another technique is to briefly halt clocking before a bright star has traversed a fraction of the rows and then restart. A new charge packet with a shorter TDI develops under the moving optical image, and is read out in the normal way. If either of these two techniques or some other proves successful, the positional accuracy between 5-8th magnitude would be 14 μas.

4.3.2 Implementation. FAME's instrument is designed and built by LMMS. Existing facilities at LMMS, such as thermal vacuum systems and clean rooms, enable most of the instrument integration, test, and calibration to be performed in one building. Some environmental tests, like vibration and EMI/EMC, are conducted in nearby facilities.

❑ *Development:* The instrument is developed as three major subsystems (see Foldout 3, Figure FO 3-2), i.e., opto-mechanical, CCD camera, and electronics. These are developed in parallel and tested at the subsystem level before integration into the completed instrument. As a first step in developing the opto-mechanical assemblies the optics specifications are finalized so that the design and fabrication can begin. During this time, the structure and optical element mounts are designed and built. As the optics are delivered, they are installed into their mounts, integrated into the structure, and aligned. The CCDs are integrated into the camera and then characterized and calibrated. The instrument computer is based on a heritage LMMS design. It will be combined with FAME-specific electronics, interfaces, power converter, and harnessing to become the FAME electronics subsystem. It is fully tested with a version of the flight S/W before integration with other FAME subsystems. The electronics are subjected to thermal cycling before integration with the completed FAME instrument.

❑ *Verification Tests:* Once the instrument is complete final system level tests begin. First a comprehensive performance test is run to obtain baseline data before acceptance testing. Next the instrument is subjected to random vibration tests in each axis to identify potential workmanship problems followed by a subset of performance tests. Finally, a thermal balance/thermal vacuum test qualifies the instrument for operation in the space environment.

❑ *Calibration:* Instrument calibration is based on a piecewise characterization of the optical elements. Established methods and existing equipment used will vary according to the elements under test. An end-to-end calibration is performed in an existing facility at LMMS before shipment to NRL for system-level integration and test.

❑ *Instrument and S/C Integration:* The instrument is processed in three major steps: (i) analytically integrate the instrument and S/C, computer simulations and physical models are used to prepare the instrument ICD and demonstrate interface compatibility; (ii) verify electrical and S/W interfaces, instrument brassboards and a "tabletop" S/C simulator are used; and (iii) integrate the instrument and S/C. Foldout 3, Figure FO 3-4 summarizes the ISU test process, starting with tests to verify that the S/C and instruments are physically, functionally, and electromagnetically compatible. After interfaces are verified, the instrument is mechanically and electrically integrated to the S/C bus and functional tests verify interface compatibility and system performance.

4.4 Spacecraft. The S/C provides coarse attitude determination and control, power, communications, and data handling. COTS subsystems will be used where practical. The S/C meets all mission requirements, including instrument electrical, mechanical, and thermal interface. During the Phase A study, we will generate detailed S/C requirements and solicit vendors for formal technical and cost inputs. Refer to Foldout 3. Figure FO 3-1 shows a block diagram of the FAME S/C. Table FO 3-1 lists power and mass estimates. Table FO 3-2 lists major components, vendors, and heritage.

4.4.1 Attitude Determination and Control Subsystem (ADCS). The ADCS supports the FAME mission through orbit transfer, initial acquisition, safe-hold, and science observation (Table 4-1). During orbit transfer, the ADCS provides coarse pointing from the sun sensor and inertial reference unit (IRU). Prior to firing of the AKM, the IRU is initialized from attitude provided by the Star Tracker (ST). During orbit trims, the vehicle spin rate is reduced and ST data is available continuously. Throughout, ADCS outputs command the hydrazine thrusters to control orientation, spin rate, and nutation. At GEO, the spin rate is further reduced to 1080 arcsec/sec and the spin axis is oriented 45 deg to the sun line, using the ST as a precise reference. The ADCS next enters a monitor mode wherein the relation between the precession rate and the sun shield sweep angle is calibrated. The sweep angle of the instrument's sun shield is then adjusted and further observations are collected. The procedure is repeated until the desired spin axis precession rate is achieved. Section 2.2.2 discusses using solar torque for spin axis precession.

Table 4-1. ADCS Characteristics

Control Method	Spin Stabilized w/Passive Damping: • Imaging: Passive precession control via solar torquing • Safehold: RCS & Sun Sensors • Acquisition & Orbit Maintenance: RCS, Sun Sensor, & IRU	
Control Reference	Solar Frame	
Agility	• Solar Torque: ±1 x 10^{-4} N-m • RCS Torque: ±1.63 N-m	
Deployments	• Solar Array and Shield	
Articulation	None	
On-Orbit Calibration	• Instrument Line-of-Sight Calibration • Solar Torque Calibration	
Ground Processing:	• Precession Torque Estimation	
Onboard Processing	• ST Image & Attitude Estimation • IRU Bias Estimation & Attitude Propagation • SS Data Processing for Aspect Angle and Coarse Spin Rate	
Control	**Requirement**	**Est. Perf.**
• Spin	20 min ±5%	Complies
• Spin Precession	10 Days ±10%	Complies
• Spin Variation	≤0.5%	≤0.05%
• Precession Variation	≤1.0 deg/hr	≤0.5 deg/hr
• Sun Aspect Angle	45±5deg	Complies
Knowledge	**Requirement**	**Est. Perf.**
• Sun Aspect Angle	≤0.5 deg	≤0.25 deg
• Inertial Attitude	≤0.1 deg	≤0.03 deg
• Transverse Rate	≤0.5 deg/hr	≤0.15 deg/hr
• Spin Rate	≤0.25 deg/hr	≤1.0 deg/hr

❑ *ADCS Components:* The relatively coarse attitude requirements allow selection of small, low-cost components. The Corning-OCA ST has heritage from *Clementine* and is baselined for ICM. It measures vehicle orientation with an error of ≤0.03 deg proving ample performance margin. Using the ST, a low-cost IRU (AlliedSignal TGA-14) can be calibrated to provide an order of magnitude improvement over the 0.5 deg/hr requirement (Table 4-1). The low S/C spin rate necessitates the use of a non-spinning sun sensor. Many of these non-spinning sun sensors can operate at spin rates exceeding 4 rpm which provides a degraded mode option should the ST fail. This option also supports attitude updates through part of the spin up and spin down operations. The sun sensor is the primary sensor during safehold activities.

4.4.2 Electrical Power Subsystem (EPS). The EPS captures, stores, and distributes energy to all S/C subsystems. It incorporates three major components: a high efficiency GaInP/GaAs/Ge solar cell array, two high specific energy 15 A-Hr NiH_2 single pressure vessel (SPV) batteries, and a Power Control and Distribution Unit (PCDU). The SPV, qualified on *Clementine*, stores energy for use during eclipses and high-power usage activities. The system uses direct energy transfer, i.e., the batteries regulate the bus. The solar array uses state-of-the-art cells providing >21.5% efficiency (3 mil coverglass). The array is sized to provide 588 W EOL (3.23 m^2 area) at the 45˚ angle between the array normal and the sunline. The PCDU (similar to Clementine's) conditions primary power, regulates battery charge control, distributes the load, protects circuits, and monitors current, voltage, and selected temperatures. Excess energy production is limited by opening the circuit to individual solar array cell strings; no shunts are used.

4.4.3 Radio Frequency (RF) Communications.

The RF communications subsystem provides the capability for simultaneous command and narrowband/wideband telemetry compatible with NASA and NRL ground stations (Foldout 4, Figure FO 4-1). It includes: a flight-proven, low-cost, high-reliability S-Band transponder (L3 Communications) for uplink and downlink; a subcarrier oscillator; a convolutional encoder; a diplexer; a power divider, and switch to minimize the effects of antenna pattern interference nulls. Multiple transmit and receive antennas ensure sustained communications when the S/C is changing attitude or in the event it tumbles. The transponder supports Pseudo-Random Noise (PRN) turnaround for ranging and navigation. When enabled, the PRN code is extracted from the uplink carrier and then phase-modulated onto the downlink baseband. The delay between transmitting and receiving this code yields the vehicle's range. Also, the uplink and downlink frequency coherence allows the S/C velocity (range-rate) to be calculated by measuring the Doppler shift. The receiver is always powered. The downlink data rate (400 kbps) is sufficient to include the average instrument data rate, overhead, and S/C housekeeping. Link calculations assume usage of CCSDS and show that the baseline data rates are achievable (Foldout 4, Table FO 4-4). RF spectrum usage is based on NASA's existing S-Band frequency allocations. Immediately upon selection, specific frequencies will be determined using NHB2570.6A guidelines.

4.4.4 Command, Telemetry, and Data Handling Subsystem. An Integrated S/C Controller (ISC) and a Solid State Data Recorder (SSDR) are used (Foldout 3, Figure FO 3-1). The ISC performs S/C processing and high-level instrument control. The SSDR stores mission data and housekeeping telemetry. ISC functions include attitude control, reaction control, guidance navigation and control, S/C commands and telemetry, downlink frame formatting, uplink command processing, and high-level instrument control. ISC's functions are performed by COTS VME-based modules inserted into a backplane consisting of a main processor, data handling unit (DHU), uplink/downlink module, S/C I/O module, power supply, and ACS/RCS module. A 4 Gigabit SSDR (sized to support communications outages and instrument buffering requirements) consists of Error Detected and Corrected (EDAC) 64 Mb DRAM modules and a microcontroller to handle input data, record control functions, and to scrub the memory for bit errors. The SSDR is controlled via a IEEE-1553 data bus and uses RS422 for high-rate data transmission.

4.4.5 Thermal Control Subsystems (TCS). The TCS uses materials and devices with extensive flight heritage. All electronics boxes are mounted on the inboard surface of the S/C structure panels, which serve as radiators to reject component heat. Radiator surfaces are taped with silver-deposited teflon. All other surfaces are covered with multi-layered insulation (MLI) blankets. Internal bus surfaces and electronics boxes are covered with high IR ε black paint. Electronics baseplate temperatures are maintained at ≤29˚C. During survival modes, heater power maintains a component temperature of ≥-10˚C. Heat exchange and thermal distortion are minimized at the structural interface with the instrument by using an interface panel that contains dedicated small capacity radiators and thermostatically controlled "spot" heaters. Each interface point is maintained to 20±2˚C. MLI is placed between the S/C and the instrument, and over all non-radiator surfaces, to minimize radiative interchange. The batteries have a separate radiator (750 cm^2) to maintain a temperature of <20˚C while discharging during eclipses. A thermostatically controlled heater maintains temperatures at >0˚C during trickle charging. The batteries and their internal mounting surfaces are covered with MLI to minimize heat exchange with the rest of the S/C. MLI and heaters are used on RCS lines, thrusters, and the propellant tank to maintain all components within required temperature limits. To prevent heat soak-back into the S/C, the entire SRM will be covered with high-temperature, aluminized beta cloth MLI covered with a single layer of aluminized Kapton.

4.4.6 Structures. The structure is a six-sided, truncated pyramid. The base of the pyramid is 2.0 m across, and the height is 1.0 m. The framework is machined aluminum and the outer shell consists of aluminum honeycomb panels. The instrument will be attached to the upper six-sided equipment panel at three locations using flexures. Flexures provide thermal isolation from the S/C and serve as a kinematic mount to eliminate bench thermal preloads. The RCS tank is mounted on the inboard surface of this same panel.

4.4.7 Mechanisms. The solar array/sun shade mechanisms consist of six deployable wings, each having two 1.0 m x 1.0 m panels to which solar cells are bonded. The panels and hinges use heritage H/W designs from *Clementine*. The design uses rigid honeycomb panels with graphite epoxy face sheets and aluminum honeycomb core. Panels are stowed in a bifold configuration with in-board panel cells exposed. Power can be generated before the array is deployed, during the S/C acquisition and initialization phases. Staggering the roller mechanism allows the outer panel to deploy after sufficient inner panel motion. Aluminized Kapton "webs" are attached between the panels. A series of constant tension springs keep the webs taut after deployment. These webs fill gaps in the rigid solar panel area completing the sun shade. The solar array/sun shade is held flat or swept downward into a conical shape to trim the center of pressure location. The shade is deployed by stepper-motor driven leadscrew struts on each of the panels.

4.4.8 Propulsion System. The propulsion system includes a STAR 30BP SRM used for final orbit insertion, and a 4:1 blowdown monopropellant (N_2H_4) reaction control system (RCS) that supports attitude control during orbit insertion, maneuvering, and provides a backup to the solar torque control. The N_2H_4 RCS was chosen for its inherent low cost and high-reliability. A single 36 cm diameter tank holds 13 kg of N_2H_4. An aluminized bladder propellant management device minimizes propellant slosh. Two clusters, each with four 0.2 lb_f thrusters, spin, despin, provide nutation control, and precess the S/C during AKM firing, and during on-orbit maneuvers including de-orbiting the ISV at the end of mission life. The thrusters provide some functional redundancy. The propellant delivery system is dual fault tolerant to leakage. The system also incorporates a pressure transducer and three service valves. The COTS design requires no component qualification to meet mission needs.

4.4.9 Flight S/W. FSW is resident on the ISC and includes algorithms for ADCS, CT&DH, EPS control, and autonomous flight operations. It is derived from *Clementine* and provides five functions:

❑ *Resource Manager:* Provides primary housekeeping and timing for S/C activities, loads and dumps memory, manages tasks, verifies processor health and status, provides an interrupt handler, a device interface to individual modules, and communication services.

❑ *Telemetry and Command Processing:* Validates uplinked commands and data, supports realtime, stored, and event driven commanding, supports variable telemetry downlink rates, formats housekeeping telemetry into packets and frames, logs telemetry packets and frames to the ISC, and logs telemetry to the SSDR.

❑ *Stored Commanding*: A COTS implementation of S/C Command Language (SCL), (used on *Clementine*) provides procedural scripts and the capability to respond autonomously via rule-based mechanisms to asynchronous events. Scripts and rules to task the S/C are generated on the ground, compiled into tokens by the SCL compiler, formatted for transmission to the S/C, and stored for subsequent execution.

❑ *GNC Processing:* Consists of the GNC executive that controls S/C modes and allowable commands. It generates the commanded attitude and updates the S/C's inertial properties. It interfaces, processes, and combines IRU and ST data; manages spin rate, precession, and nutation during spin stabilized flight; and controls the thrusters.

❑ *GNC Image Processing:* The GNC Image Processing module includes the S/W necessary to match a ST image to an onboard star catalog to determine attitude, provide auto-exposure for the cameras, centroid on objects in the field of view of the cameras, and detect the Earth's limb.

4.5 Launch Vehicle. A Delta 7425 ELV places the S/C into a GEO transfer orbit (185 x 35,786 km) at a 28.7° inclination. The ELV configuration uses a 2.9 m fairing with four strap-on Alliant graphite-epoxy motors to augment first-stage performance and a Star-37FM solid rocket motor (SRM) third stage. A Star-30BP SRM is used as an AKM to raise the perigee of the transfer orbit to the final circular GEO at 35,786 km. Our mission analysis shows that 510 kg (408 kg with 25% contingency) can be delivered to GEO, providing 15% margin on the ELV's capability and 17% on the AKM. Once the ELV delivers the ISV to the transfer orbit, the assembly is despun using existing ELV capabilities. A V-Band separation system separates the space vehicle and ELV. The ISV is trimmed using the S/C's ADCS; when it nears apogee, the ISV is spunup, and the AKM fires to raise the perigee and circularize to a GEO orbit.

4.6 Ground Systems. The Mission Operations system includes a control center, a dedicated 10 m antenna, and FAME's Science Data Processing Center. These USNO facilities are linked to an alternate command and control antenna site at NRL's Blossom Point facility. The Control Center is accessible via the Internet.

❑ The UCC operates the S/C and its instrument, while the Flight Operations Team (FOT) performs mission planning, commanding, health monitoring, and engineering support. The UCC is developed entirely from COTS H/W and S/W (e.g., ITOS, EPOCH 2000, COMET, and FreeFlyer). The S/W is modified to meet mission-specific requirements. Within the UCC, a Front-End Processor (FEP) serves as the interface between the FAME RF elements and the UCC baseband digital elements. Table 4-2 lists the major FEP functions. During Phase A, we will evaluate the feasibility and cost of linking the UCC to the NASCOM system to provide alternate data paths for telemetry, command, tracking, voice, and file transfers.

❑ The primary ground station is continually in-view of FAME's "figure-eight" orbit track (Foldout 4, Figure FO 4-2). The station supports both autotrack and program-track. The antenna supports S-Band downlink at data rates of 400 Kbps (instrument and engineering telemetry) and command links of 2 Kbps. Link margins are provided in Foldout 4, Table FO 4-1. Blossom Point link margins are better due to the 15.8 m antenna. Before the manufacturer's final acceptance testing, the transponder is tested for compatibility with the ground station. These tests are repeated during integration and test activities.

Table 4-2. Front-End Processor Functions

• Communications Interface to Primary (USNO) and Secondary (Blossom Point) RF elements
• Level 0 processing on received data packets
• Data "splitting" and "routing" to appropriate destinations
• Archiving of all raw data packets
• Capability to play back "raw" data from archives for reprocessing or to support testing (e.g., new algorithms, calibrations, anomaly identification and resolution)
• Standardized Graphical User Interface (GUI) for commanding, telemetry display, and processing evaluation
• Interface to other UCC systems via LAN

4.7 MO&DA. USNO and Omitron provide a Flight Operations Team (FOT) to monitor S/C health and welfare. The FOT is also represented during early program phases to ensure that operational considerations and life-cycle costs are part of the development process. The FOT participates in the Integration and Test process, and will develop operations procedures. They participate in integrated end-to-end tests and simulations to verify interfaces and mission scenario execution. The S/C and instrument developers participate in the engineering evaluation and checkout (EE&C) phase, as well as periodic reviews of system status after launch. Initial on-orbit operations are carefully scripted to activate and evaluate S/C and instrument performance. S/C and instrument experts supplement the FOT to support EE&C; the UCC is staffed continuously until EE&C is completed.

4.7.1 Flight Operations. The FOT consists of a flight ops lead, a S/C systems engineer, a H/W and S/W ground systems engineer, mission planning engineer, and an instrument team/ science team planner. A small group of S/C and instrument developmental engineers augment the FOT for launch and special operations. During critical operations and maneuvers (i.e., launch, AKM burn), a team of subsystem specialists is located at the UCC to resolve anomalies immediately. By the end of EE&C, the developmental engineers will provide a complete Orbital Operations Handbook to document all S/C and instrument operational modes and constraints. Throughout the mission, a S/C engineer and an instrument engineer are "on-call" to resolve anomalies. If an anomaly occurs, the S/C engineer ensures that the S/C is in a safe mode and that a specialist is contacted to resolve the problem. COTS S/W monitors health and status and is capable of limit checking, automatic trending, and inference engine rules functions. Operators verify S/W execution, analyze results, investigate anomalies, and respond to "off-nominal" situations. The FOT performs flight dynamics actions such as sun shield adjustment, star catalog updates, and nominal calibrations. It also performs orbit determination and propagation to support science mission planning and survey status tracking. Activities include sun/umbra predictions for power, antenna pointing, and constraint analyses.

4.8 Mission Assurance. FAME uses COTS and previously qualified H/W and S/W to minimize risk and system design cost. Foldout 3, Table FO 3-2lists major H/W components and vendor sources. COTS procurements result in minimal requalification of components with the commensurate cost savings.

❑ At the selected orbit, the annual radiation dosage is due primarily to trapped electrons with only negligible contributions by protons and solar flares. Using GFSC's Orbital Flux Study (Barth), the annual total ionizing dose (TID) is calculated at 250 kRad (Si) behind 100 mil Al over a 2.5 year mission. The design incorporates EEE parts and appropriate "spot" shielding to enable operation at these levels. Designs incorporate mitigation approaches for single event effects (SEE).

❑ Reliability calculations for the single string design, along with degraded modes and functional redundancy are planned during Phase A studies.

4.8.1 Assembly, Integration, and Test. Foldout 3, Figure FO 3-4 shows fabrication, integration, and test flow. Manufacturing personnel are involved throughout the development cycle. A functional electrical test serves as the acceptance and buy-off baseline for the S/C and for the instrument. Functional tests verify the integrity and functionality of all normal and redundant components, connectors, component-to-component I/Fs, vehicle-to-GSE I/Fs, vehicle-to-ELV I/Fs, and component, subsystem, and system power consumption. Abbreviated functional tests are performed before, during, and after environmental tests. After the acceptance test (buy-off), the S/C and instrument are mated. After mechanical mating, harness continuity is tested. S/C electrical harnesses are then mated with instrument connectors. After harness connection, satisfactory I/F compatibility is verified. After mating, critical I/F tests are performed that verify proper signal characteristics, limited performance tests, and final calibrations

4.8.2 Verification and Environmental Test. An incremental design verification and test program provides visibility for cost, schedule, and technical performance issues. Emphasis is placed on performance-based testing, early verification of design and environmental predictions, and demonstrated test margins. The systems engineer defines, coordinates, publishes, and controls the system-level test verification requirements. An Integrated Product Development Team (IPDT) verifies requirements and develops tests, analyses plans, and procedures to integrate, test, and verify components. A tailored MIL-STD-1540 test approach verifies system-level requirements with demonstrated margins. A protoflight qualification program is baselined.

4.8.3 Quality Assurance. Our quality system uses the guidelines of ANSI/ASQC Q9001-1994 and GSFC-410-MIDEX-003. Table 4-3 summarizes our planned approach. MIL-STD-882 guidelines are used to define risk levels. FAME complies with all appropriate environmental regulations.

4.8.4 Systems Engineering. The IPDT process defines, maintains, and verifies requirements. It consists of the PI, PM, S/C and Instrument lead en-

Table 4-3. Mission Assurance Approach

• ***Reliability Assurance*** addresses design, fabrication, and test. Worst Case, Reliability, and Failure Modes and Effects Analysis at the interface level, are baselined. • ***Quality Assurance*** is integrated with design, procurement and fabrication. • ***EEE Parts*** selection uses GSFC 311-INST-001 for quality, reliability, TID, and single event effects (SEE). • **Materials and Processes** are certified for compliance with safety requirements and for outgassing requirements. • ***Test Verification*** uses a verification and environmental test matrix and appropriate procedures to ensure the instrument and S/C meet the mission requirements. A protoflight environmental qualification test program is baselined. • **Contamination** budgets are developed, and appropriate controls are specified using NRP-1124 guidelines. • ***Software QA*** supports internal and external development to validate requirements, design, and interfaces.

gineers, along with the Science Team. The IPDT performs requirement analyses and trade studies, defines Level-1 requirements, and allocates these to FAME subsystems. Developmental processes follow NPG7120.5a guidelines. Periodic reviews and Science Working Group meetings, including the seven milestone reviews of NPG7120.5a, are baselined. Design and test history reviews determine suitability for use. Specifications, prepared during Phase B, identify interface and physical requirements, constraints, and performance characteristics. Test plans ensure that subsystems meet requirements. Engineering models are used to understand subsystem integration and to mitigate design interface issues. FAME's change control process follows MIL-STD-973 and DoD-STD-498 guidelines. Configuration is managed through development, integration, test, and launch. Documentation is accessible via the Internet. Specialty engineers ensure that design standards are met. Lead engineers integrate, check out, and verify the S/C and instrument, including calibrations. Functional and performance tests verify that systems have been successfully integrated. During the prelaunch phase, team members support integration and testing of the ISV. We support integrated activities occurring during launch processing.

4.8.5 Trade Studies and New Technology. Preliminary system-level trades have been completed to define a baseline approach; more trades are planned during Phase A and B. Specific instrument and S/C trades (Table 4-4) are directed at reducing cost and risk at the systems level. Because we are using existing H/W and processes, no new technology is required for the FAME S/C bus.

Table 4-4. Phase A S/C Trade Studies

Selected Baseline	Alternatives
• S-Band Downlink	• X-Band Downlink
• NiH_2 Energy Storage	• Lithium Ion
• Conventional Al Structure	• Selective Use of Composites to lower Mass
• Single-String Design	• 2 Transponders w/ Limited Processor Redundancy
• No Star Tracker Cover	• Star Tracker Cover using *Clementine* Design
• USNO Groundsite	• Use of existing NASA Ground Sites

4.8.6 Risk Management. We have identified three risk areas for FAME that may impact cost, schedule, or performance. These are listed in Table 4-5. Our risk abatement plans, funded in our baseline costs, virtually eliminate these risks. Risk management also may involve using reserves and descope options. A formal and quantified risk analysis is performed in Phase A and updated for quarterly reviews in Phase B/C/D.

Table 4-5. Risk Mgmt. and Descope Options

Risk Area	Risk (H/M/L)	Descope Option
Solar Torque Precession of the Spin Axis	M	**Conventional ACS & RCS**
Short Focal Length Instrument Design	M	**Longer Focal Length Instrument**
Single String Design	M	**Reduced Mission Life**

4.8.7 Technology Development Plans. FAME has intentionally taken a low-risk, COTS approach to maximize the science return per dollar expended. No new technology items are baselined. If required, new technology H/W is flight-qualified through tailored tests and analyses with an emphasis on test verification. Design and test history reviews determine suitability for use in a spaceflight application.

Table FO 3-1. Mass and Power

Subsystem	Total Mass (kg)	Power (W)	
		Peak	OAP
FAME Instrument	165.0	250	220
S/C Bus			
CT&DH	13.5	60	30
Comm	4.3	40	40
EPS	24.4	15	15
Ordnance	5.0	10	0
ADCS	22.8	32.6	32.6
RCS	24.1	0	0
TCS	10.0	80	16
Structures	101.4	0	0
Booster Adapter	13.6	0	0
Ballast	13.6	0	0
Harness	9.1	0	0
AKM	453.0	0	0
Totals			
Instrument	165.0		220
Spacecraft Bus	241.8		143.6
Total S/C w/ AKM	859.8		363.6
Contingency (25% Mass & 50% Pwr)	101.7		181.8
Total S/C w/ Contingency	961.6		545.4
LV Capability & Avail. Pwr	1132		588.1
Margin On AKM & Power	16.9%		7.3%
Launch Vehicle Margin	15.0%		—

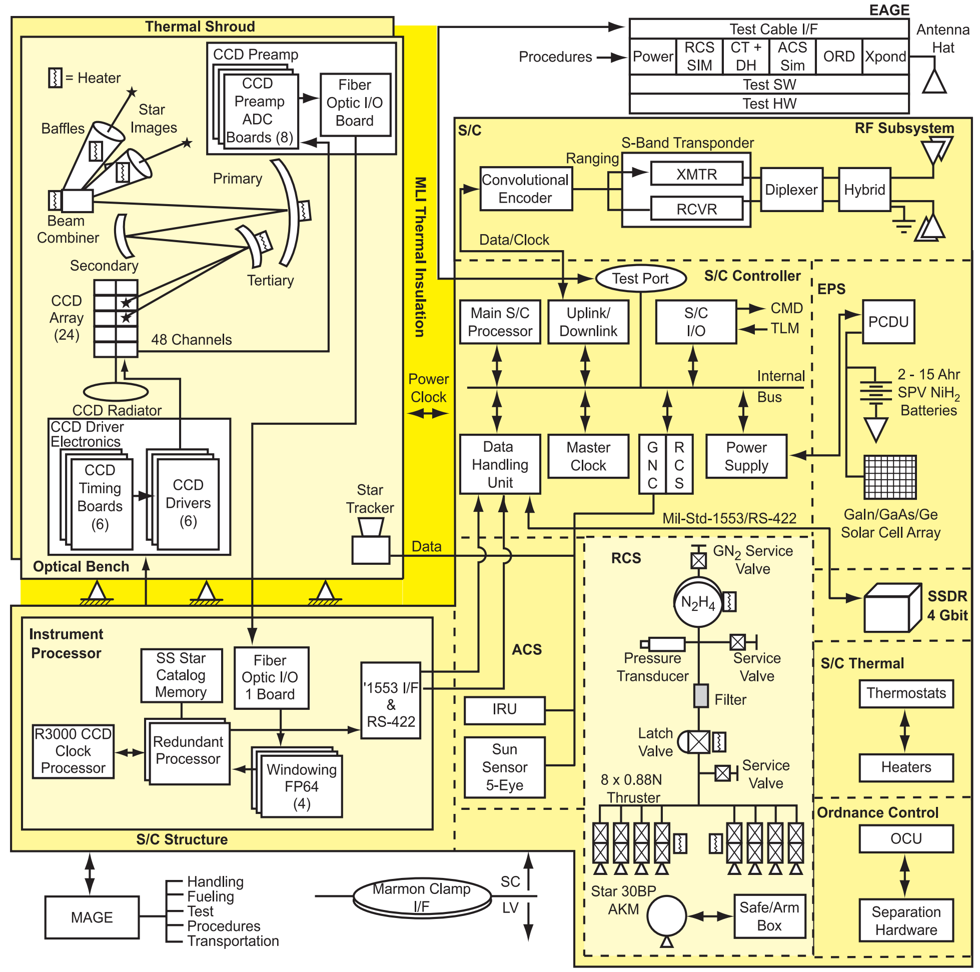


Figure FO 3-1. Block Diagram

Table FO 3-2. Component Heritage

CT&DH	• ISC - R6000 COTS Processor Card-set - Lockheed - Multiple Missions • ISC Support Cardsets - MOTS • SSDR - COTS - Seakr - *Clementine* / Multiple Missions
COMM	• XPDR - COTS - L3, Inc. - *Clementine* • Antenna - MOTS - *Clementine*
EPS	• Solar Array Panels/Hinges: *Clementine, NTS* • Battery: COTS - *Clementine*, *Iridium* • PDCU: Custom - *Clementine* Multi-junction Solar Cells: COTS - Tecstar - *STEX*
OCS	• MOTS- *Clementine*
ADCS	• Star Tracker: COTS - Corning-OCA - *Clementine* and NRL's ICM Program • IRU: COTS - AlliedSignal TGA-14 - *Iridium* • Sun Sensor: COTS - Adcole - Multiple Missions
RCS	• AKM: COTS - STAR 30BP - Multiple Missions Thrusters: Marquardt - Multiple Missions
TCS	• Custom- Multiple Mission
Structures	• S/C Bus and Booster Adaptor: custom; Conventional materials - *Clementine*

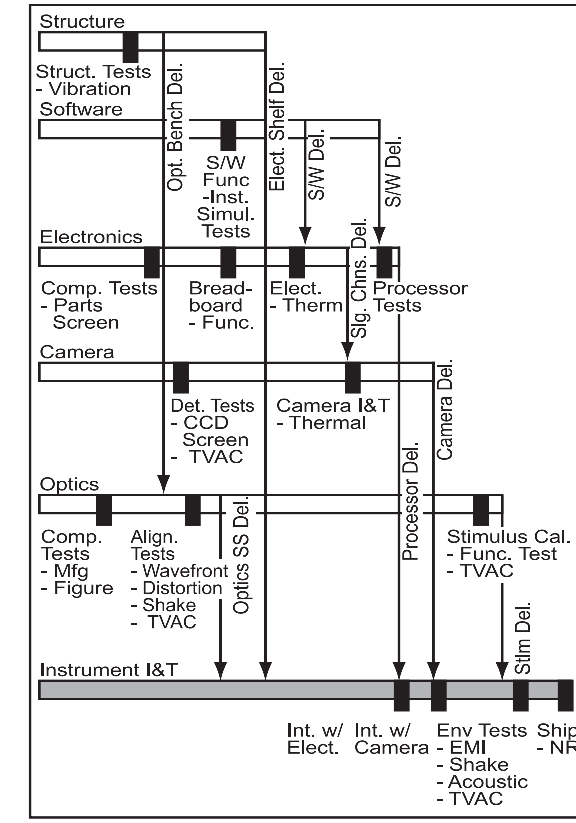
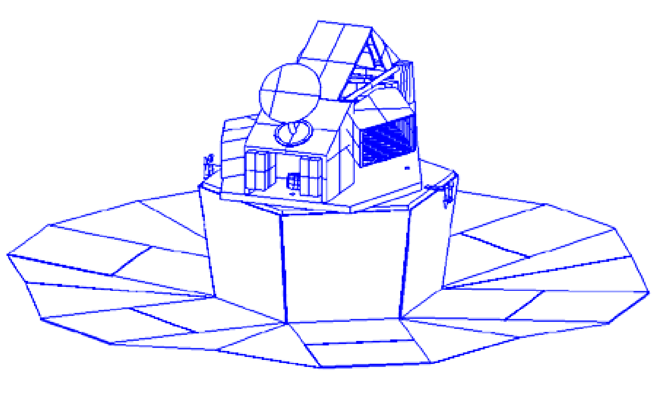


Figure FO 3-2. Instrument Integration



Instrument Cover Removed

Figure FO 3-7. On-Orbit Configuration

Figure FO 3-6. ISV (Cutaway)

Instrument Cover Removed

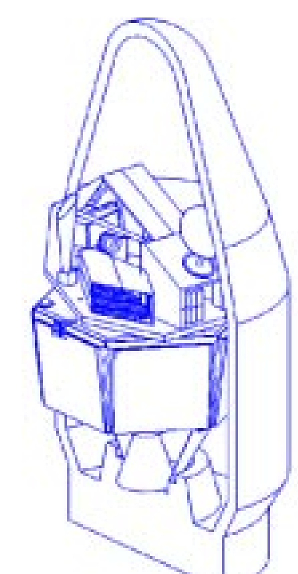


Figure FO 3-5. ISV in 2.9m Fairing

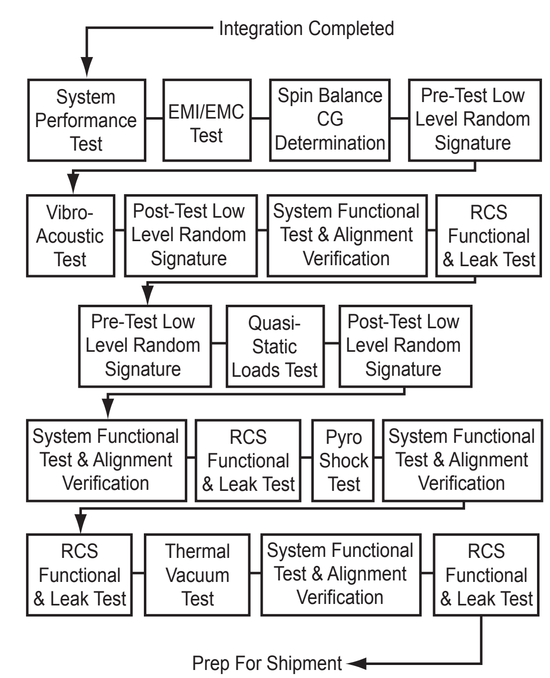


Figure FO 3-4. Integration and Test

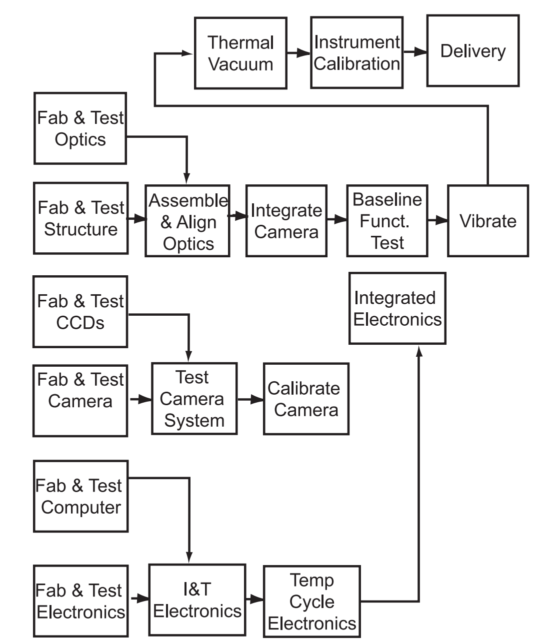


Figure FO 3-3. Instrument Development Flow

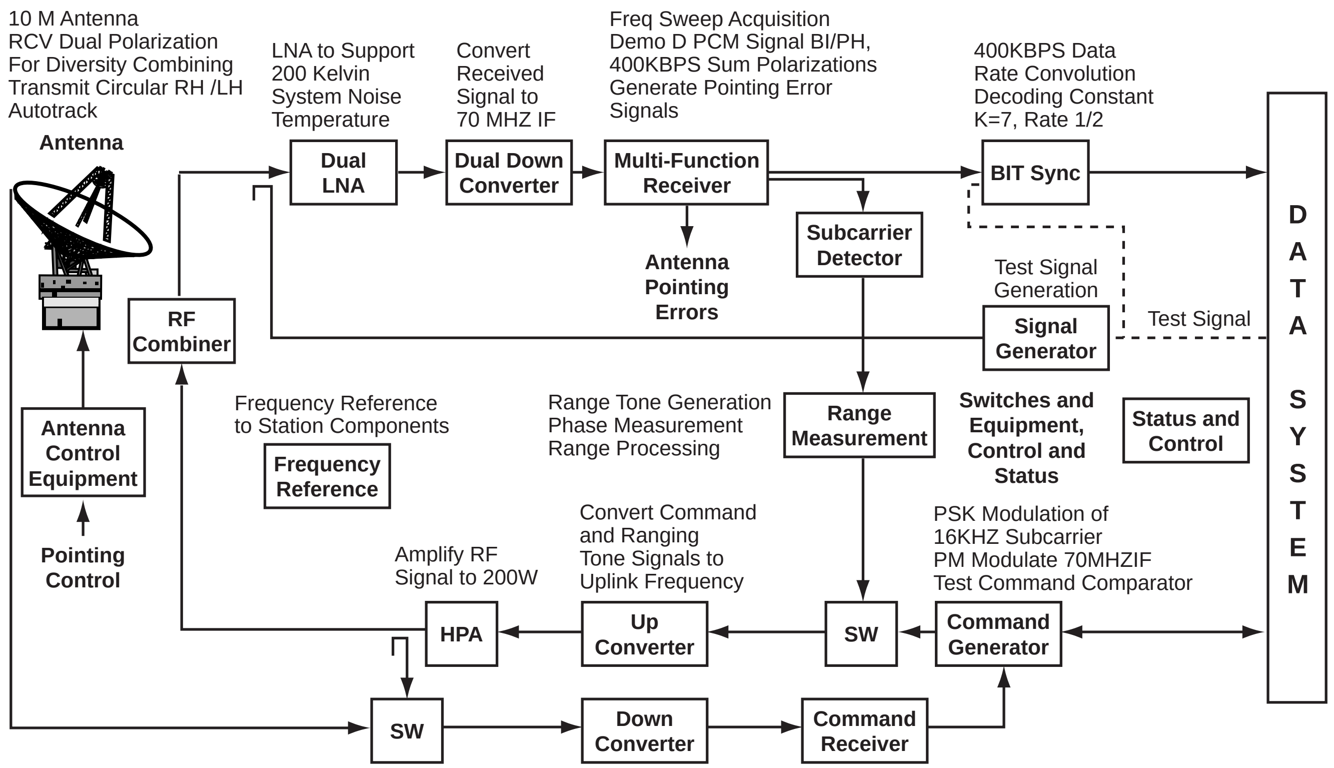


Figure FO 4-1. FAME Ground System

Table FO 4-5. Error Budget - Single Measurement

Source	Error (microarcsec) [1] a priori	Error (microarcsec) [1] a posteriori	Notes
Photon Statistics • V=9 • V=15 • Read noise, 7 e⁻rms, V=15	 540 10800 6600	 540 10800 6600	(1) A priori and a posteriori refer to the error before and after modeling (fitting) using iterative astrometric data reductions. The a posteriori errors are dominated by photon statistics, and all will be largely uncorrelated from one epoch to another. To arrive at the values in Foldout 1, Table FO-3, the photon statistics plus residual errors are divided by the square root of the number of measurements, with a small quantity added in quadrature (10 microarcsec) to account for correlations. (2) Due primarily to Solar radiation pressure on the shield, whose reflectivity varies spatially (we assume 1% over 1 m2). The rotation error varies smoothly over a rotation, and changes very little from one rotation to the next. Therefore, it can be modeled to very high accuracy. Somewhat more difficult to model is the rotation error due to Earth radiation (reflected and reradiated) entering the viewports, which causes a rotation variation of order 20 µas, but the torque varies according to which instrument structures are illuminated, and the weather on Earth. Data from a single rotation suffice to model the spacecraft attitude to the level shown.
QE Variation	560	<10	
CCD Wavelength-Dependent Absorption	300	30	
Charge Transfer Effects	800	80	
Incorrect Stellar Spectrum Model	4000	50	
Undetected Companions	60	60	
Onboard Clock Error	<10	<1	
Telescope Geometry Changes	100	<10	
Optical Distortion	2000	20	
Refraction in CCD Cover Plate	1	<1	
Rotation Rate Changes	10^6 [2]	<1	
Ephemeris (1 cm/sec knowledge)	7	<1	

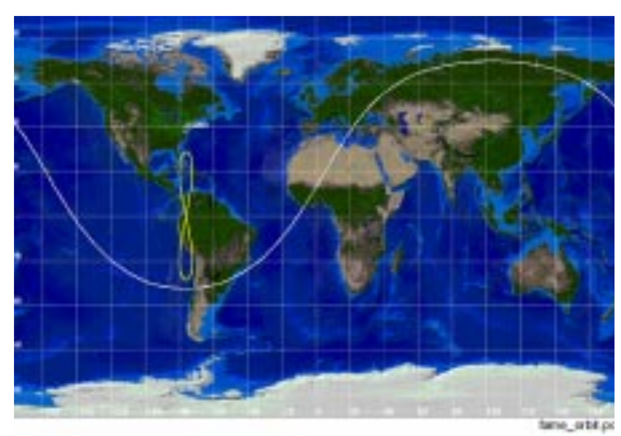


Figure FO 4-2. Ground Track

Table FO 4-2. Orbit Selection and Maintenance

Launch Date	• March, 2003
Mission Duration	• 30 Months
Orbit Type	• Geosynchronous (35,786 km) • 28.7 deg Inclination
Nominal LAAN	• 282 deg East; places S/C over USNO & NRL • ± 45.8 deg of nominal elevation value
Ground Track	• Slant Range varies from 35,900 to 37,340 km • Elevation varies from 15 to 78 deg
RAAN	• Annual drift rate of 4.3 deg West
Station-keeping	• Periodic station-keeping maneuvers (every 4 to 6 weeks) must be performed to maintain longitudinal position

Table FO 4-3. Uplink & Downlink Information

Downlinked Data Volume (GB/day)	• 34 Gb/Day
Link Margins (USNO Site)	• 5.2 dB (Uplink) • 5.1 dB (Downlink)
Onboard Storage (MB)	• 4 Gigabits
Transmit Power	• 10 W (Downlink)
Data Dumps per Day	• Continuous (GEO)
Data Destination	• USNO (S/C Data, and Science)
Uplinks per Day	• Continuous (30 min/day reserved for ranging)
Data Rates	• 2 kbps (Uplink) • 400 kbps (Downlink)
Frequency	• 2070 MHz (Uplink) • 2247 MHz (Downlink)
Modulation	• BPSK (Uplink) • PCM/BPSK/PM (Downlink)

Table FO 4-4. Performance and Margin Summary

Design Parameter	Desired	Actual
Mass at Separation	20 to 30%	25%
Power (EOL)	15 to 20%	57%
Pointing Accuracy	x1.5	x1.5
Knowledge Accuracy	x1.5	x2.0
Propellant Loading	20 to 25%	60%
Data Throughput	20 to 30%	25%
Data Storage (3 hrs Req'd)	40 to 50%	100%
RF Link Margin (Downlink)	6 dB	5.1 dB
Structural F.S. (ultimate)	1.4	1.4
Deployment Torque Factor	x4	x4

• Data Obtained from NASA's Mission Design Process, GSFC 12/94

Table FO 4-1. Link Margins (10 m)

DOWNLINK		
Satellite Altitude (km)	35,786	
XMT Freq (MHz)	2250.0	
XMT Pwr (W)	10.0	
XMT Line Loss (dB)	0.5	
XMT Antenna Gain (dB)	0.0 (Omni)	
Rcvr G/T dB/K	21.0	
Data Rate (Mbps)	0.4	
Implementation Loss (dB)	3.0	
Theoretical Eb/No (dB) [R=1/2, K=7; RS (255,223)]	4.0	
Range (km)		37,340
XMT Pwr (dB)		40.0
- Line Loss (dB)		-0.5
XMT Antenna Gain (dBi)		0.0
- Path Loss (dB)		-191.0
- Atmospheric Loss (dB)		0.0
Rcvr G/T (dB/K)		21.0
- Boltzman's Constant (dBm/Hz/K)		198.6
Eb/No (dB/Hz)		12.1
- Total, Required Eb/No (dB)		-7.0
Data Margin (dB)		5.1
UPLINK		
Satellite Altitude (km)	35,786	
XMT Freq (MHz)	2071	
XMT EIRP (dBm)	95.0	
Carrier Modulation Loss (dB)	2.7	
Data Modulation Loss (dB)	4.5	
CMD Data Rate (b/s)	2000	
Ranging Modulation Los (dB)	13.8	
Rcv Antenna Gain (dBi)	-10.0	
Rcv Line Loss (dB)	2.0	
Required C/No (dBHz)	48.8	
Required Eb/No (dBHz)	20.0	
Rcvr Noise Figure (dB)	4.5	
Range (km)		37,340
XMT EIRP (dBm) Min.		95.0
- Path Loss (dB)		-190.3
- Atmospheric Loss (dB))		0.0
Rcv Antenna Gain (dBi)		-10.0
Rcv Line Loss (dB)		-2.0
Rcvd Signal (dBm))		-107.3
Rcvd Carrier (dBm)		-110.0
Rcvr Noise Density (dBmHz)		-170.0
C/No (dBHz)		60.0
Required C/No (dBHz)		-48.8
Carrier Margin (dB)		11.2
Received Data (dBm)		-111.8
Eb/No (dB/Hz)		25.2
-Required Eb/No (dBHz)		-20.0
Data Margin (dB)		5.2

5. Management and Schedule

FAME's management team contains the scientific, technological, and managerial expertise to execute this challenging mission on cost and schedule.

5.1 Organization. FAME uses a Principal Investigator (PI) model for management (Figure 5-1).

❑ The PI, Dr. Johnston, USNO's Scientific Director, is accountable to NASA/GSFC for the FAME mission, including on-time and on-budget delivery of the instrument, spacecraft, ground data analysis system, and archival data products. He guides the mission's scientific aspects; organizes and leads the science team and scientific investigation, including prompt reduction and dissemination of data to the scientific community. He is responsible to achieve science objectives defined in this proposal and to recommend termination if these objectives cannot be met within cost and schedule reserves.

❑ The Project Manager (PM), to be designated during Phase A, is responsible to the PI for developing mission elements to a consistent set of requirements, supporting the Level 1 baseline agreed upon by the Science Team, and assuring the budget and schedule are met. The PM is responsible for instrument and S/C delivery, integration and test, support to the launch vehicle, and initial on-orbit evaluations. A Technical Advisory Board provides the PM with specific capabilities needed to carry out the science mission.

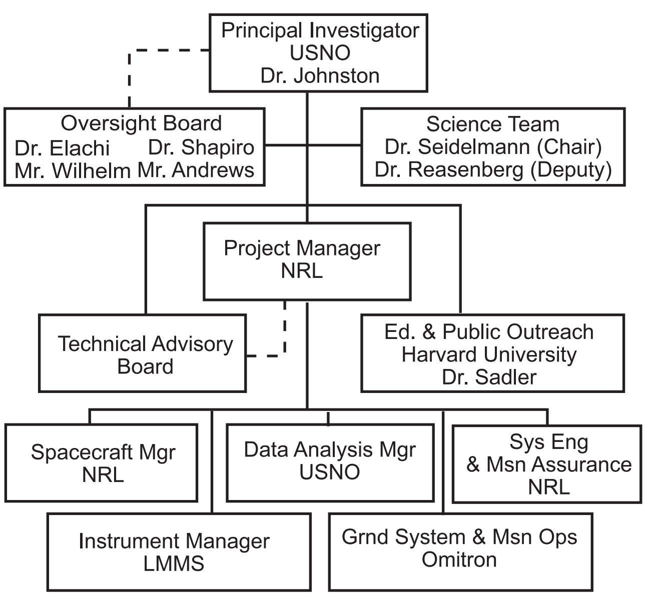


Figure 5-1. Management Organization

❑ A Management Oversight Board, comprised of senior executives, assures that mission institutional activities are aligned and resolves top-level issues that conventional project management mechanisms cannot successfully resolve.

❑ The Science Team defines and monitors scientific mission requirements. It is chaired by Dr. Seidelmann, with Dr. Reasenberg as deputy, both of whom report directly to the PI. Table 2-4 lists the Science Team members and their specialties.

5.2 Management Approach. FAME stresses cost containment. Realistic requirements will be set to satisfy the baseline science investigation achievable within cost and schedule risk. Clear lines of accountability make a person, not an organization, responsible for each program element. The partnering institutions stress a "badgeless team" approach, and maintain a systems engineering focus throughout definition, development, and test activities. Complete, accurate and timely programmatic forecasts and reports make development aspects visible project-wide. Risk mitigation plans are developed early, and current descope paths maintain cost and schedule integrity. Frequent and rapid communication using e-mail and video conferencing ensures coordination of all project elements.

5.3 Teaming, Capabilities, and Experience. FAME's participants have the extensive and relevant experience required to execute the diverse program elements successfully. The PI is the Scientific Director of the USNO, one of the world's leading institutions in the field of astrometry. The USNO scientists involved in this mission have developed precise catalogs of star positions, as illustrated by the ACT Reference Catalog (Urban et al. 1998). SAO scientists pioneered space astrometry with the concept for the POINTS mission. Engineers from Lockheed Martin and NRL are experts in spacecraft instrumentation with expertise in thermal stability and low-cost small satellite missions, respectively (Table 5-1).

5.4 Roles and Responsibilities. Institutional and individual roles and responsibilities are clearly delineated (Table 5-1 and Table 5-2). Each individual overseeing a project element reports to the PM. Designated System Engineering and Mission Assurance personnel conduct requirements analysis

Table 5-1. Major Team Member Responsibilities and Experience

USNO	Lead/PI's institution for FAME investigation: Navy scientific mission includes measuring UTC, Earth's rotation, positions and motions of celestial objects, and assembling these data into star catalogs. Extensive facilities include astrometric telescopes and radio/optical interferometers. Lead for data processing, analysis, and catalog.
NRL	Lead for Program Management, spacecraft, payload integration, and launch processing: Navy's corporate research laboratory with an extensive history of space systems development, including over 80 individual satellites and 32 launches. Executing agency for LACE (1990), *Clementine (1994)*, TiPS (1995), ATEx (1998), and ISS's ICM (1999).
LMMS	Lead industrial partner for developing, testing, and calibrating FAME instrument: Builder of many successful instruments; proven expertise in imaging and spectroscopic instrumentation operating from X-ray to optical wavelengths, including OSO-MXRH, SMM-XRP, SOHO/MDI TRACE, SIRTF, SXT, and sounding rocket payloads.
SAO	Lead for data verification and algorithm development: Developed concept design for POINTS and FAME instrument.
IPAC	Lead for photometric processing. Processing center for 2 MASS survey data and IRAS data.

and verification, specialty engineering, and quality assurance activities. Design reviews and safety studies are concurrent with design and fabrication of the instrument, the spacecraft, and processing for launch. Verification by test is emphasized and a failure reporting system is included.

5.5 Risk Management. Descope options follow agreed-upon processes. Identifiable descope decision points and criteria are developed during Phase A. If mission descope is considered, the PM provides the PI with a set of decision options and recommended actions. After consulting with the Science Team and the NASA MIDEX program office, the PI determines the appropriate course of action. Descope strategies and risk areas are discussed in Sections 1.4.1 and 4.8.6, respectively. The PI holds all mission reserves.

5.6 Program Schedule. The master schedule (Figure 5-2) establishes task interrelationships, time phasing of events and key activities. The PI oversees the schedule and the PM executes it. The schedule includes two months of funded reserve.

Table 5-2. Management & Advisory Boards

Scientific Direction and Mgmt.	• PI, Dr. Johnston, USNO, Project Oversight and Scientific Direction; Final Authority for Mission Success • PM, To Be Designated, NRL, Program Execution, Business Management and S/C Development
Science Team Coordination	• Dr. Seidelmann; USNO; Science Team Chairman • Dr. Reasenberg; SAO; Science Team Deputy Chairman and Project Scientist
Technical Advisory Board	• Mr. Johnson; Omitron; Ground System and Flight Ops • Dr. Germain; USNO; Error Analysis • Mr. Mook; NRL; Spacecraft Manager • NRL; Systems Engineer & Msn Assur. • Mr. Urban; USNO; Data Analysis Manager • Dr. Vassar; LMMS; Instrument Manager • Dr. Horner; USNO; Proposal Manager • Dr. Greene; LMMS; Instrument Scientist

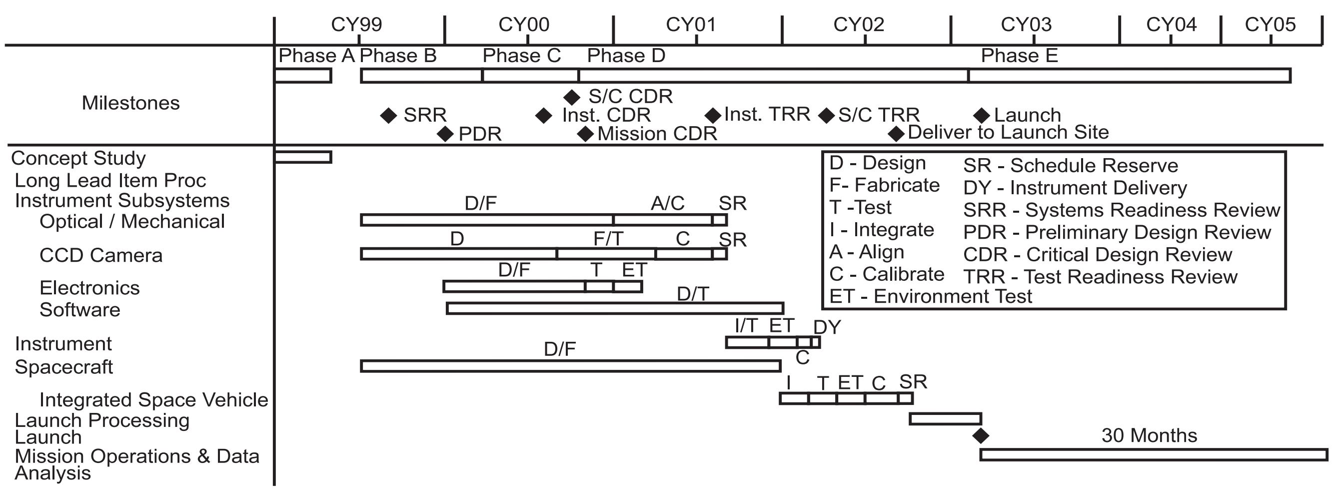


Figure 5-2. FAME Program Master Schedule

6. Cost and Cost Estimating Methodology

6.1 Total Mission Cost. This section provides FAME cost data and describes the cost estimating methodology. Table 6-1 contains FAME cost summary data in constant FY98 dollars. Table 6-2 describes costing assumptions. Table 6-3 provides Total Mission Cost data and Table 6-4 summarizes cost data by mission phase.

Table 6-1. FAME Program Costs

Item	1998 $K	
	Cost-to-Launch	Total Mission Cost
Phase A Cost	350.0	350.0
Cost to Launch (Phase B - D)	78,678.8	78,678.8
NASA Launch Services		43,118.6
Phase E Costs		16,024.8
Totals	79,028.8	138,172.2

6.2 Cost Buildup. NASA's WBS serves as the FAME cost estimating framework. All data were developed from a build-up of tasks and purchased items. Costs are based on engineering experience and vendor quotations. Required cost categories (direct labor hours and dollars, materials, subcontracts) are estimated using the WBS and Master Schedule. A detailed month-by-month breakdown was made for civil service and contractor staffing, supplies, equipment, services, and travel for each program phase. NASA's inflation indices were applied, and the total costs were summarized. Full costing of all civil service support is included. USNO is operationally funded. USNO billing rates for civil service employees include hourly direct labor rates, fringe rates, and overhead burdens. NRL is classified as a Navy Working Capital Fund Agency (NWCFA); all direct project costs, including salaries, are derived from project funds. Overhead burdens are applied only to civil servant salaries. Non-salary expenses are unburdened. Direct costs associated with major contracts are included as procurement surcharges. NRL uses a stabilized billing rate for civil service employees that includes hourly direct labor rates, fringe rates, production rates, and General and Administrative (G&A) rates.

6.2.1 Ground Rules and Assumptions. Table 6-2 summarizes major costing assumptions.

Table 6-2. Costing Assumptions

FAME uses tailored requirements of NPG7120.5a, Project Management Processes and Requirements
Phase A award by Jan 99. Phase B awarded by June 99.
FAME instrument and S/C are costed as a "Level 3" mission using NASA GFSC 311-INST-001 guidelines.
Use of "Grade 2" EEE parts and MIL-STD-883 equivalent devices. Residual flight spares, and commercial/industrial parts can be used. Only selective EEE parts screening is baselined.
USNO and NRL costs use "full cost accounting" for all civil service and support contractors.
NASA contracts directly for launch services under the current Med-Lite Contract.

6.2.2 Acquisition and Procurements. During Phase A, FAME performs a "make or buy" analysis that uses a "best-value" approach incorporating schedule, cost, performance, mission assurance, and risk. The PM is responsible for acquisitions. To ensure SB/SDB goals are met, USNO's Business Manager monitors all procurements. Competitive procurements and firm-fixed-price contracts are used if possible. When selected for Phase B, USNO will consider performance-based fee plans for the instrument and ground segment contracts.

Instrument costs are based on a proposal received from LMMS. USNO will contract directly with LMMS for this effort. Ground station costs are based on a proposal received from Omitron, Inc. S/C and project management costs are based on an NRL estimate. No fee is proposed on these costs and funding will be via USNO Military Interdepartmental Procurement Request (MIPR). The S/C costs assume that the NRL is Prime Contractor. During Phase A, alternate contracting methods will be studied, including NASA GFSC Rapid S/C Development Office (RSDO). USNO funds all Co-Investigators activities. NASA field activities will be separately contracted by NASA.

6.2.3 Manage and Control Reserves. Planning and program organization efforts are based on the WBS and the master schedule. The WBS serves as a framework for budget definition, program reporting, and control. The PI approves the WBS and budget that are continuously updated to reflect current status. The PI must approve any changes in scope, funding, or performance.

- ❑ *Descope:* Section 1.4.1 lists possible mission descopes should cost overruns occur.
- ❑ *Reserve:* A 13% reserve for the Phase C/D Design and Development was used.

A. FAME's Statement of Work (SOW)

This appendix contains the sample Statement of Work (SOW) between the National Aeronautics and Space Administration (NASA) and the U.S. Naval Observatory (USNO) for conduct of the Full-sky Astrometric Mapping Explorer (FAME) as a MIDEX project as described in AO 98-OSS-03. Lockheed Martin Missiles and Space (LMMS) Advanced Technologies Corporation, Smithsonian Astrophysical Observatory (SAO), and Naval Research Laboratory (NRL) are partners on this project, and their efforts, which will be contracted from USNO, are included in the SOW.

A.1 Phase A—Concept Definition Phase Study. During Phase A, FAME project personnel will investigate and refine the proposal's conceptual designs in the following specific areas:

a. The error budgets will be verified. The accuracies from present models will be tested using the real point spread functions and the selected CCDs. The optical design will be reviewed and further optimized. Study results will provide the basis for selecting the telescope focal length/plate scale that produces maximum scientific return for the FAME mission.

b. The instrument, specifically the optical bench, will undergo a more detailed thermal analysis to verify the preliminary study performed during the proposal phase.

c. A cost and data accuracy trade-off study of the geosynchronous orbit versus alternative orbits will be performed. This includes launch, transmission, onboard storage costs, and achievable data rates.

d. Design and deployment of the solar radiation shield and precession control will be reviewed to determine if trim mechanisms are needed to adjust the control and correct for any changes due to shield aging.

e. The optimum method of reading out the observational data from the CCDs, storing and tagging the data, modeling the PSF, and centroiding the images will be investigated in more detail. This includes trade-offs of an input catalog versus thresholding, onboard processing versus transmission to the ground, variable readout rates for the chips, and dealing with crowded fields in the galactic plane.

f. Instrument and spacecraft designs (e.g., thermal, electrical, etc.) will be reviewed for possible improvements, and for potential weight and cost reductions.

g. USNO will develop a detailed implementation plan and a firm cost plan for all FAME mission aspects. The conceptual design presented in the proposal will be refined, detailed performance specifications will be developed, and the mission implementation plan will be refined. The results of the Phase A study will be documented in a Concept Definition Phase Study Report.

h. The concept definition study shall conclude with a commitment by the PI on the total cost, schedule, and scientific performance of the FAME Mission.

A.2 Phase B—Preliminary Design. During Phase B, the USNO will lead the FAME preliminary design effort.

a. Internal and external interfaces will be established and documented. The design will be developed with LMMS Advanced Technology Center and NRL to ensure the instrument and spacecraft fulfill mission requirements and are compatible with the launch vehicle.

b. Ground Support Equipment (GSE) and software preliminary designs will be developed to assess design adequacy.

c. The design, including software requirements and architecture, will be fully documented.

d. The deliverables include documentation necessary for the Mission Design Review and System Description. This includes block diagrams, engineering drawings, flight operation plans, requirements, and architectural design documents. Long-lead items required for the FAME mission will be identified and procurement will begin as necessary.

A.3 Phase C—Design Phase. During Phase C, USNO will develop the FAME instrument and spacecraft detailed designs to the level permitting fabrication of all subsystems.

a. Long-lead items will be ordered and fabrication will begin immediately upon approval of the detailed designs. Coordination with participating institutions continues—particular attention will be given to early definition of mechanical, electrical, and software interfaces among subsystems provided by different institutions.

b. The spacecraft and instrument integration plan will be developed.

c. The system engineering analysis will be updated.

d. The flight and GSE software design will be completed, software will be developed, and a final command list and telemetry definition will be released.

e. Deliverables include documentation for the critical design review and system integration plan, including hardware and software detailed design documents.

A.4 Phase D—Development Phase. During Phase D, the USNO will lead the FAME development, integration, and test efforts.

a. Subsystems will be assembled and tested before integration. Subsystems will be integrated into a complete system and tested.

b. Integration and test activities will occur in a cleanroom environment.

c. Flight and ground software coding will be completed and software will be tested with the instrument and GSE.

d. Acceptance testing will be performed in accordance with the verification plan.

e. The spacecraft and instrument will be tested and accepted before integration begins. Integration will be completed and acceptance tests performed.

f. The spacecraft will be delivered for integration on the launch vehicle.

g. USNO will develop the ground station, workstations, and software needed to control the FAME mission launch. These systems will be tested by conducting simulated operations and compatibility tests with the spacecraft before launch.

h. USNO will support the launch and initial 30 day on-orbit commissioning of FAME.

i. Deliverables include detailed drawings, test procedures, flight instrument and spacecraft, flight and ground software, GSE, and readiness review data packages.

A.5 Phase E—Mission Operations and Data Analysis (MO&DA). During Phase E, FAME project personnel will provide mission operations activities and data archiving and dissemination.

a. The spacecraft and instrument will be checked out for nominal operation. Rotation and precession rates of the spacecraft will be adjusted.

b. The observation program will begin along with verification of data reduction procedures.

c. Spacecraft status and operation documentation will be provided.

d. Software tools necessary for data analysis and reduction will be refined and associated documentation updated.

e. Data will be archived and made available to the public.

B. Letters of Endorsement

C. Resumes

John N. Bahcall

Education:

Ph.D. (physics), Harvard University, 1961.

Professional Employment:

Indiana University, Research Fellow in Physics, 1960-1962.

CalTech, Res. Fellow, Asst. Prof., Assoc. Prof. of Physics, 1962-1970.

Institute for Advanced Study, Member 1968-1969 (term II), 1969-1970; Professor 1971-present.

Princeton University, Visiting Lecturer with rank of Professor, 1971-present.

Honors and Awards:

Warner Prize American Astronomical Society, 1970; Sloan Foundation Fellow, 1968-1971.

National Academy of Science, American Academy of Arts and Sciences, Member, 1976.

Shulamit Goldhaber Lecturer, Tel Aviv University, 1987.

James Arthur Prize Lecturer, Harvard-Smithsonian Center for Astrophysics, May 1988.

NASA Distinguished Public Service Medal, 1992.

The Jessie and John Danz Lectureship, University of Washington, May 1992.

Academia Europaea, Member 1993; Nevada Medal of Science, 1994.

Dannie Heineman Prize, Amer. Inst. Phys./ Amer. Ast. Soc., 1994.

Award Medal, University of Helsinki, 1996.

Hans Bethe Prize, American Physical Society, 1998.

Group and Committee Memberships:

Space Telescope Working Group, At-Large Member, Interdisciplinary Scientist, 1973-1992.

American Astronomical Society, Councillor, President 1978-1981, 1990-1992.

National Academy of Science, Chair, Section on Astronomy, 1980-1983.

National Academy of Sciences, Chair Astron. and Astrophys. Survey Committee, 1989-1991.

National Academy of Sciences, Chair Panel on Neutrino Astrophysics, 1994-1995.

U.S. National Committee of the International Astronomical Union, Chair, 1996-1998.

Recent Relevant Publications:

Unsolved Problems in Astrophysics, eds. Bahcall and Ostriker, 1997, (Princeton University Press).

Solar Neutrinos: The First Thirty Years, eds. J. Bahcall, R. Davis, P. Parker, A. Smirnov, and R. Ulrich, 1995, (Addison-Wesley).

The Decade of Discovery in Astronomy and Astrophysics, J. Bahcall, Chair, and NAS Survey Committee Members, 1991, (National Academy Press).

Neutrino Astrophysics, 1989, (Cambridge University Press).

Arp, H., & Bahcall, J. 1973, The Redshift Controversy, ed. G. Field (Addison-Wesley).

Dr. Christian de Vegt

Education:

Ph.D., University of Hamburg, 1966.

Experience:

Dr. de Vegt is a professor of astronomy at the University of Hamburg since 1979. From 1966 to 1979, Dr. Christian de Vegt held various academic positions at the University of Hamburg/Hamburg Observatory. His main scientific research areas are astrometry, in particular, photographic astrometry, astrometric catalogs, and the extragalactic reference frame. He is a member of the Astronomische Gesellschaft and IAU. he was involved in the ESA HIPPARCOS Astrometry Satellite Mission as a member of the Input Catalog Consortium, Program Selection Committee and extragalactic reference link working group. From 1991-1994, he was president of IAU Commission 24 Photographic Astrometry and chairman of the IAU WG on extragalactic reference frame. His present research activities are optical observing programs of extragalactic reference frame sources and various catalog projects based on Hipparcos and Tycho data.

Publications:

de Vegt, Chr. Reports on Astronomy 1991-1993: Commission 24 Photographic Astrometry. Reports on Astronomy, J. Bergeron ed. 1994, 22A;225-228.

Fey, A.L., Russell, J.L., de Vegt, Chr., Zacharias, N., Johnston, K.J., Ma, C., Hall, D.M., Rolenried, E.R., “A Radio-Optical Reference Frame VI” Additional Source Positions in the Northern Hemisphere. Astron J., 1994, 107, 385.

Russell, J.L., Reynolds, J., Jauncey, D.L., de Vegt, Chr., Zacharius, N., Ma, C., Fey, A.L., Johnston, K.J., Hindsley, R., Hughes, J.A., Malin, D.F., White, G., Kavaguchi, N., Takahashi, Y., “A Radio-Optical Reference Frame V” Additional Source Positions in the Mid-Latitude Southern Hemisphere. Astron, J. 1994, 107, 379.

Johnston, K.J., Fey, A.L., Zacharius, N., Russell, J.L., Ma, C., de Vegt, C., Jauncey, D.L., Reynolds, J.E., Archinal, B.A., Carter, M.S., Eubank, Nicholson, G., Sovers, O.J., Schaffer, D., “A Radio Reference Frame” Astron, J., 110, No.2, p. 880-915, 1995.

Zacharius, N., de Vegt, C., Winter, L., “A Radio-Optical Reference Frame VIII, CCD-Observations from KPNO and CTIO” Internal Calibrations and First Results, Astron, J., 110, No. 6, p. 3093-3106, 1995.

Russell, J., Fey, A., Jauncey, D., Johnston, K., Kawaguchi, N., Kemball, A., King, E., Ma, C., Macleod, G., Malin, D., McCulloch, P., Nicolson, G., Reynolds, J., Shaffer, D., Takahashi, Y., de Vegt, C., White, G., Zarcharius, N., Proc. Conf. Subarcsecond Radio Astronomy, Manchester, 1992, Davis, R.J., Booth, R.S., eds. Cambridge UP, p.397-402., 1993.

de Vegt, C., The Hipparcos and Tycho Catalogues, Vol. 1-17, ESA SP-1200, in particular, VOl. I and III, 1997.

Walter, H.G., Hering, R., de Vegt, C., “Radio Stars for Linking Celestial Reference Frames” Astron. Astrophys. Suppl. 122, No. 3, p. 529-532, 1997.

Kovalevsky, J., de Vegt, C., “The Hipparcos Catalogues as a Realization of the Extragalactic Reference System, Astron. Astrophys., 322, p. 620-633, 1997.

de Vegt, C., Morrison, L.V., WGM3 International Catalog Projects, IAU Highlights Astronomy Vol. 10, p. 683-687, WG Comm. 24, 1995.

Zacharius, N., de Vegt, Chr., Murray, C.A., CPC2 Plate Reduction with Hipparcos Stars. First Results In: Battrick B., Perryman, M., Bernacca, P.L., eds, HIPPARCOS 97 Venice. ESA-SP 402, p. 85, 1997.

George Gatewood

Education:

B.A., Astronomy, University of South Florida, 1965.

M.A., Astronomy, (University Scholar's Award) University of South Florida, 1968.

Ph.D., Astronomy, Zaccheus Daniel Fellowship) University of Pittsburgh, 1972.

Employment:

Joint Appointment, Department of Geology and Planetary Science, University of Pittsburgh, 1989-present.

Professor, Department of Physics and Astronomy, 1989-present.

Associate Professor, Department of Physics and Astronomy, 1978-1989.

Director, Allegheny Observatory, University of Pittsburgh, 1977-present.

Assistant Professor, Department of Astronomy, 1972-1976.

Professional Awards and Activities:

National Aeronautics and Space Administration, 1993, for contributions to the Astrometric Imaging Telescope.

National Space Act Award, 1987, for the invention of the Multichannel Astrometric Photometer.

Chairman, Extrasolar Planetary Foundation, 1994-present.

Principal Investigator, The Allegheny Observatory Search for Planetary Systems, 1977-present.

Principal Investigator, The Allegheny Observatory Trigonometric Parallax Program, 1974.

Principal Investigator, The Characterization of Planetary Systems, 1996-present.

Principal Investigator, A High Precision Version of the MAP, 1995-present.

Professional Organizations:

American Astronomical Society, Divisions of Dynamical Astronomy, Planetary Science.

International Astronomical Union, Commissions on Astrometry, Binary Stars, Life Sciences.

Recent Publication:

Gatewood, G., Klewlet de Jonge, J., and Persinger, T., "Correlation of the Hipparcos and Allegheny Observatory Parallax Catalogs," Astronomical Journal, 116, 1998.

Gatewood, Snyder-Hale, Snyder-Hale, Persinger, McMillan, Montanii, Moore, and Perry, "A New Instrument for the Characterization of Extrasolar Planetary Systems," Planets Beyond the Solar System and the Next Generation of Space Missions, ed D. Soderblom, Astronomical Society of the Pacific, conference publications, 119, 41, 1997.

Gatewood, G. and Han, I., "A MAP Based Study of ADS 14893" Astronomical Journal, 110, 1880, 1995.

Gatewood, G. and Klewlet de Jonge, J., "MAP-Based Trigonometric Parallaxes of Altair and Vega, Astrophysical Journal, 450, 364, 1995.

Gatewood, G., "MAP Based Trigonometric Parallaxes of Altair and Vega" Astrophysical Journal, 445, 712, 1995.

Han, I. and Gatewood, G., "A Study of the Accuracy of Narrow Field Astrometry Using Star Trails taken with the CFHT," Publications of the Astronomical Society of the Pacific, 107, 399, 1995.

Gatewood, G., Klewlet de Jonge, J., and Heintz, W.D., "Astrometric Studies in the Region of Algol," Astronomical Journal, 109, 434, 1995.

Gatewood, G., "A Study of the Astometric Motion of Barnard's Star,' Astrophysics and Space Sciences, 223, 91, 1995.

Gatewood, G. and Klewlet de Gonge, J., "MAP Based Trigonometric Parallaxes of Open Clusters: The Praesepe," Astrophysical Journal, 426, 166, 1994.

Gatewood, G., "One Milliarcsecond Precision Studies in the Regions of the Binary Stars O Equulel and X^1 Orionis," Publications of the Astronomical Society of the Pacific, 106, 138, 1994.

Gatewood, G., Klewlet de Jonge, J., and Stephenson, B., "One Milliarcsecond Precision Parallax Studies in the Regions of O Cephel and EV Lacertae," Publications of the Astronomical Society of the Pacific, 105, 1101, 1993.

Gatewood, G., Klewlet de Jonge, J., and Stephenson, B., "Multichannel Astrometric Photometer Parallax Studies in the Regions of Groombridge 1616, Bootlis, and O Draconis," Astronomical Journal, 105, 1179, 1993.

Andrew Gould

Education:

Ph.D. (Physics), Stanford University, 1988.

B.Sc. (Mathematics), Stanford University, 1971.

Professional Employment History:

Professor, Ohio State University, 1996-present.

Assistant Professor, Ohio State University, 1993-1996.

Postdoctoral Fellow, Institute for Advanced Study, 1988-1993.

Actuary, William M. Mercer, San Francisco, 1982-1984.

Body Sealer, Ford Motor Co., Milpitas, CA, 1973-1981.

Honors and Awards:

1994 recipient of Alfred P. Sloan Fellowship.

Recent Relevant Publications:

Gould, A., "MACHO Parallaxes From A Single Satellite," 1995, ApJ, 441, L21

Nemiroff, R. J. & Gould, A., Probing For MACHOs of Mass 10^{-15} M to 10^{-7} M with Gamma-Ray Burst Parallax Spacecraft, 1995, ApJ, 452, L111

Gould, A., Bahcall, J. N., & Flynn, C., M Dwarfs From Hubble Space Telescope Star Counts III: The Groth Strip, 1997, ApJ, 482, 913

Gould, A. & Gaudi, B. S., Femtolens Imaging of a Quasar Central Engine Using a Dwarf Star Telescope, 1997, ApJ, 486, 687

Palanque-Delabrouille, N. et al., Microlensing towards the Small Magellanic Cloud. EROS 2 first year survey, 1998, A&A, 332, 1

Gould, A., & Popowski, P., Systematics of RR Lyrae Statistical Parallax III: Apparent Magnitudes and Extinctions,1998, ApJ, 508, 000

FAME Participation:

Dr. Gould will focus on using FAME proper motions and parallaxes to extract information about Galactic structure, with primary emphasis on determining the mass density and mass profile of the Galactic disk. Dr. Gould has considerable experience in this area dating back to 1989. His most recent paper on this subject is listed above, Gould, Bahcall, & Flynn (1997).

Thomas P. Greene

Education:

Ph.D. (Astronomy), University of Arizona, 1991.

Certificate, University of Arizona, Graduate Optics Short Course, 1985.

B.A. (Physics), University of California at Santa Cruz, 1982.

Professional Employment:

Research Scientist, Lockheed Martin Missiles and Space Advanced Technology Center, Palo Alto, CA (Manager of SIRTF and NGST Instrumentation Development), 1997

Division Chief, NASA Infrared Telescope Facility, and Associate Astronomer, University of Hawaii Institute for Astronomy, Honolulu, HI, 1996- 97

Assistant Astronomer, U. H. Institute for Astronomy NASA IRTF Cryogenic Echelle (CSHELL) Spectrograph Project Scientist, 1992-96.

National Research Council Research Associate, NASA Ames Research Center, Moffett Field, CA. 1991-92

Graduate Research and Teaching Assistant, University of Arizona, Tucson, AZ, 1985-91

Research Engineer and Software Engineer, Nanometrics Inc., Sunnyvale, CA, 1983-85

Group and Committee Memberships:

American Astronomical Society.

Astronomical Society of the Pacific.

Society of Photo-Optical Instrumentation Engineers.

Recent Relevant Publications:

Wilking, B. W., Greene, T. P., & Meyer, M. R., Spectroscopy of Brown Dwarf Candidates in the rho Ophiuchi Molecular Core, 1998, ApJ, submitted

Mainzer, A., Greene, T., Young, E., et al., The Pointing Calibration and Reference Sensor for the Space Infrared Telescope Facility, 1998, Proc. SPIE, in press

Greene, T. P. & Lada, C. J., Near-Infrared Spectra of Flat-Spectrum Protostars: Extremely Young Photospheres Revealed, 1997, AJ, 114, 2157

Greene, T. P. & Joseph, R. D., The NASA Infrared Telescope Facility, 1997, BAAS, Annual Observatory Report

Greene, T. P. & Lada, C. J., Near-Infrared Spectra and the Evolutionary Status of Young Stellar Objects: Results of a 1.1 - 2.4 mm Survey, 1996, AJ, 112, 2184

Watarai, H., Hayata, E., Matsumoto, T., Takahashi, H., Tutui, Y., Yoda, H., Matsuhara, H., & Greene, T. P., MIRFI: A Mid-Infrared Fabry-Perot Imager, 1996, PASP, 108, 1033

Greene, T. P. & Meyer, M. R., An Infrared Spectroscopic Survey of the rho Ophiuchi Young Stellar Cluster: Masses and Ages from the H-R Diagram,1995, ApJ, 450, 233

Greene, T. P., Tokunaga, A. T., Toomey, D. W., & Carr, J. S., CSHELL: A High Spectral Resolution 1 - 5 micron Cryogenic Echelle Spectrograph for the IRTF, 1993, Proc. SPIE, Vol. 1946, p. 313

Witteborn, F. C., Greene, T. P., Wooden, D. H., & Cohen, M., Future Airborne IR Spectrometers: Improved Efficiency and Calibration, 1993, in Astronomical Infrared Spectroscopy: Future Observational Directions, ed. S. Kwok, A. S. P. Conference Series 41, p. 365

Greene, T. P. & Young, E. T., Near-Infrared Observations of Young Stellar Objects in the rho Ophiuchi Dark Cloud, 1992, ApJ, 395, 516

FAME Participation:

Provide scientific oversight of the construction of the FAME instrument; also study the earliest stages of pre-main-sequence stellar evolution using FAME observations of young stellar clusters.

Scott D. Horner

Education:

Ph.D. (Astronomy and Astrophysics), University of Chicago, 1994.

M.Sc. (Astronomy and Astrophysics), University of Chicago, 1988.

B.Sc. (Physics and Astronomy), University of Michigan, 1987.

Honors and Awards:

1994 recipient of the Chrétien International Research Grant.

Professional Employment:

Astronomer, U.S. Naval Observatory, Astrometry Department, 1998-present.

Medium Resolution Spectrograph Instrument Scientist (Research Associate), Pennsylvania State University, Department of Astronomy and Astrophysics, 1996-1998.

U.S. Project Manager (Research Associate), Pennsylvania State University, Department of Astronomy and Astrophysics, 1994-1996.

Project Scientist (Research Associate), Pennsylvania State University, Department of Astronomy and Astrophysics, 1993-1994.

Recent Relevant Publications:

Brown, T. M., Kotak, R., Horner, S. D., Kennelly, E. J., Korzennik, S. G., Nisenson, P., & Noyes, R. W., Exoplanets or Dynamic Atmospheres? The Radial Velocity and Line Shape Variations of 51 Pegasi and Tau Bootis, 1998, ApJS (in press)

Brown, T. M., Kotak, R., Horner, S. D., Kennelly, E. J., Korzennik, S. G., Nisenson, P., & Noyes, R. W., A Search for Line Shape and Depth Variations in 51 Pegasi and Tau Bootis, 1998, ApJL, 494, L 85

Kennelly, E. J., Brown, T. M., Kotak, R., Sigut, T. A. A., Horner, S. D., Korzennik, S. G., Nisenson, P., Noyes, R. W., Walker, A., & Yang, S., The Oscillations of Tau Pegasi, 1998, ApJ, 495, 440

Noyes, R. W., Jha, S., Korzennik, S. G., Krockenberger, M., Nisenson, P., Brown, T. M., Kennelly, E. J., & Horner, S. D., A Planet Orbiting the Star Rho Coronae Borealis, 1997, ApJL, 483, L 111

Brown, T. M., Kennelly, E. J., Korzennik, S. G., Nisenson, P., Noyes, R. W., & Horner, S. D., A Radial Velocity Search for p-mode Pulsations in η Bootis, 1997, ApJ, 475, 322

Horner, S. D., The Search for Pulsations in Four Late-type Giants, 1996, ApJ, 460, 449

John P. Huchra

Education:

Ph.D. (Astronomy), California Institute of Technology, 1977.

SB, (Physics), Massachusetts Institute of Technology, 1970.

Professional Employment:

Senior Astronomer, Smithsonian Astrophysical Observatory, 1989-present.

Professor of Astronomy, Harvard University, 1984-present.

Associate Director, Center for Astrophysics, 1989-1998.

Astronomer, Smithsonian Astrophysical Observatory, 1978-1989.

Center Fellow, Harvard-Smithsonian Center for Astrophysics, 1976-1978.

Recent Relevant Publications:

Huchra, J., Hubble's Constant, 1992, Science, 256, 321

Mould, J., Huchra, J., Bresolin, F., Ferrarese, L., Ford, H., Freedman, W., Han, M., Harding, P., Hill, R., Hoessel, J., Hughes, S., Illingworth, G. Kelson, D., Kennicutt, R., Madore, B., Phelps, R., Saha, A., Silbermann, N. Stetson, P., & Turner, A., Limits on the Hubble Constant from the Distance of M100, 1995, ApJ, 449, 413

Kennicutt, R., Stetson, P., Saha, A., Kelson, D., Rawson, D., Sakai, S., Madore, B., Mould, J., Freedman, W., Bresolin, F., Ferrarese, L., Ford, H., Gibson, B., Graham, J., Han, M., Harding, P., Hoessel, J., Huchra, J., Hughes, S., Illingworth, G., Macri, L., Phelps, R., Silberman, N., Turner, A., & Wood, P., The HST Key Project on the Extragalactic Distance Scale XIII. The Metallicity Dependence of the Cepheid Distance Scale, 1998, ApJ, 498, 181

Hill, R., Ferrarese, L., Stetson, P., Saha, A., Freedman, W., Ford, H., Graham, J., Hoessel, J., Han, M., Huchra, J., Hughes, S., Illingworth, G., Kelson, D., Kennicutt, R., Bresolin, F., Harding, P., Turner, A., Madore, B., Sakai, S., Silbermann, N., Mould, J., & Phelps, R., The Extragalactic Distance Scale Key Project V. Photometry of the Brightest Stars in M100 and the Calibration of the WFPC2, 1998, ApJ, 496, 648

Macri, L., Huchra, K., Stetson, P., Silberman, N., Freedman, W., Kennicutt, R., Mould, J., Ferrarese, L., Ford, H., Graham, J., Han, M., Harding, P., Hill, R., Hoessel, J., Hughes, S., Illingworth, G., Madore, B., Phelps, R., Saha, A., & Sakai, S., The Extragalactic Distance Scale Key Project XVIII. The Discovery of Cepheids and a New Distance to N4535 Using the Hubble Space Telescope, 1998, ApJ, submitted

William H. Jefferys

Education:

Ph.D. Yale University, 1965.

M.S., Yale University, 1964.

B.A. (Astronomy), High Honors & High Distinction, Wesleyan, 1962.

Professional Employment:

Chairman, Department of Astronomy, University of Texas, 1994-1998.

Harlan J. Smith Centennial Professor, 1985-present; Professor, 1979-1985; Associate Professor, 1968-1979; Assistant Professor, 1966-1968; University of Texas at Austin.

Instructor, Wesleyan University, 1964-1965.

Honors and Awards:

National Aeronautics and Space Administration Medal for Exceptional Scientific Achievement, 1992.

Research Grants:

"Space Telescope Project—Astrometry Team," NASA Contract NAS8-32906, $5,588,482, 1978-1990.

"GSFC Hubble Space Telescope Guaranteed Time Observation Program," NASA Contract NAS5-29285, $2,709,410, 1986-1991.

"Hubble Space Telescope Astrometry Science Team Guaranteed Observing Time Program," NASA Grant NAG5-1603, $8,026,785, 1991-1998.

Group and Committee Memberships:

Vice-chair (1980-81) and chair (1981-82), Division on Dynamical Astronomy of the AAS.

Recent Relevant Publications:

Jefferys, W. H., On the Method of Least Squares, 1980, AJ, 85, 177-181

Jefferys, W. H., On the Method of Least Squares II, 1981, AJ, 86, 149-155

Jefferys, W. H., Fitzpatrick, M. J., & McArthur, B. E., GaussFit—A System for Least Squares and Robust Estimation, 1988, Celestial Mechanics, 41, 39-49

Jefferys, W. H., Robust Estimation When More Than One Variable Per Equation of Condition has Error, 1990, Biometrika, 77, 597-607

Berger, J. & Jefferys, W. H., The Application of Robust Bayesian Analysis to Hypothesis Testing and Occam's Razor, Journal of the Italian Statistical Society, 1992, 1, 17-32

Benedict, G. F., Nelan, E., Story, D., McArthur, B., Whipple, A. L., Jefferys, W. H., Duncombe, R. L., Hemenway, P. D., Shelus, P. J., van Altena, W., Girard, T., Franz, O. G., & Fredrick, L. W., Astrometric Performance Characteristics of the Hubble Space Telescope Fine Guidance Sensors, Publications of the Astronomical Society of the Pacific, 1992, 104, 958-975

Jefferys, W. H., Whipple, A. L., Wang, Q., McArthur, B., Benedict, G. F., Nelan, E., Story, D., & Abramowicz-Reed, L., 1993, Optical Field Angle Distortion Calibration of FGS3, Calibrating the Hubble Space Telescope, eds. J. Chris Blades & Samantha J. Osmer, 353-374 (Baltimore: Space Telescope Science Institute)

Whipple, A. L., Jefferys, W. H., Wang, Q., McArthur, B., Benedict, G. F., Nelan, E., Story, D., & Abramowicz-Reed, L., 1993, Maintaining the FBS3 OFAD Calibration with the Long-Term Stability Test, Calibrating the Hubble Space Telescope, eds. J. Chris Blades & Samantha J. Osmer, 375-379 (Baltimore: Space Telescope Science Institute)

Benedict, G. F., McArthur, B., Nelan, E., Story, D., Whipple, A. L., Jefferys, W. H., Wang, Q., Shelus, P. D., Hemenway, J., McCartney, J., van Altena, W. F., Duncombe, R., Franz, O. G., & Fredrick, L.W., Astronomy with Hubble Space Telescope Fine Guidance Sensor Number 3: Position-Mode Stability and Precision, Publications of the Astronomical Society of the Pacific, 1994, 106, 327-336

Benedict, G., Jefferys, W., McArthur, B., Nelan, E., Whipple, A., Wang, Q., Story, D., Hemenway, P., Shelus, P., van Altena, W., Franz, O., Duncombe, R., & Fredrick, L., 1995, Hubble Space Telescope: A Generator of Sub-Milliarcsecond Precision Parallaxes, Astronomical and Astrophysical Objectives of Sub-Milliarcsecond Optical Astrometry, eds. E. Hog & P. K. Seidelmann, (D. Reidel & Co.), 89-94

Jefferys, W. H. & Ries, J. G., 1997, Bayesian Analysis of Lunar Laser Ranging Data, Statistical Challenges in Modern Astronomy II, eds. J. Babu and E. Feigelson, (New York: Springer-Verlag), 49-63

Kenneth J. Johnston

Education:

Ph.D. (Astronomy), Georgetown Univ., 1969.

B.S.E.E., Manhattan College, 1964.

Experience: Dr. Johnston's career has been devoted to Astrophysical and Remote Sensing of celestial and earth based phenomena. He is an expert in astrometric measurements of celestial objects at optical and radio wavelengths. He pursued research in centimeter wavelength astronomy, studying the physics of molecular clouds that give rise to star formation using single telescopes and high angular resolution techniques like radio interferometry using connected link antennas and Very Long Baseline Interferometry (VLBI). He developed astrometric techniques at radio wavelengths using interferometry eventually resulting in a radio reference frame based on extragalactic radio sources with accuracies of 0.1 milliarcsecond. He has applied VLBI's astrometric techniques to optical wavelengths with the Navy Prototype Interferometer. This instrument is the first imaging optical interferometer and measures star positions over large angles to a milliarcsecond. Dr. Johnston has extensive experience in managing large programs. While at the Naval Research Laboratory (NRL), he was Chief Scientist and Director of the Center for Advanced Space Sensing, Superintendent for both the Remote Sensing Division and the Space Systems Technology Department. He currently serves as Scientific Director for the U.S. Naval Observatory, with responsibility for the Navy's precise time, time interval and astrometry programs.

Awards and Honors:

Sigma Xi Award for Pure Science, NRL, 1985

Alexander von Humboldt Senior Scientist Award,1985

Max Planck Research Award,1990

Group and Committee Memberships:

Member, American Astronomical Society

Member, International Astronomical Union

Member, International Union of Radio Science

Member, Royal Astronomical Society

Visiting Committees for the National Radio Astronomy Observatory,

Northeast Radio Astronomy Cooperation, and

Fachbeirat of the Max Planck Institut fur Radioastronomie

National Academy of Science Committees on Space Science and Astronomy

Subcommittees Interferometry and Radio Astronomy for the NAS Report on Astronomy for the 1990s

Recent Relevant Publications:.

Johnston, K. J. & Hobbs, R. W., Distribution and Brightness in Polarization of Taurus A and Brightness Distribution of NGC 1976 at 9.55 mm Wavelength, 1969, ApJ, l58, 145

Johnston, K. J., Knowls, S. H., Sullivan III, W. T., Moran, J. M., Burke, B. F., Lo, K. Y., Papa, D. C., Papadopoulos, G. D., Schwartz, P. R., Knight, C. A., Shapiro, I. I., & Welch, W. J., An Interferometer Map of the Water Sources in W49, 1971, ApJ, (Letters), 161, L21

Johnston, K. J., Wolfe, A. M., Broderick, J. M., & Condon, J. J., 3C286; A Cosmological QSO?, 1976, ApJ (Letters), 208, L47

Johnston, K. J. & Wade, C. M., Precise Positions of Radio Sources V. positions of 36 Sources Measured with a Baseline of 35 KM, 1977, AJ, 82, 701

Johnston, K. J., Elvis, M., Kjer, D., Shen, B. S, Radio Jets in NGC 4151, 1982, ApJ, 262, 61

Johnston, K. J., Palmer, P., Wilson, T. L., & J. H. Beiging, The Distribution of 6 Centimeter H2CO in the Orion Molecular Cloud, 1983, ApJ (Letters), 273, L65

Johnston, K. J., Florkowski, D. R., Wade, C. M., & deVegt, C., Stellar Radio Astrometry III, Preliminary Comparison of the Radio Reference Frame and the Optical FK4 Reference Frame by Use of Stellar Radio Emission, 1985, AJ, 90, 2387

Johnston, K. J., Spencer, R. E., Swinney, R. W., & Hjellming, R. M., The 1983 Radio Outburst of Cyg X-3: Relativistic Expansion at 0.35c, 15 Oct 1986, ApJ, 309, 694

Johnston, K. J., Gaume, R., Stolovy, S., Wilson, T. L., Wamsley, C. M., & Menten, K. M., The Distribution of 62-61 and 52-51 Type Methanol Masers in OMC-1, 1992, ApJ, 385, 232

Johnston, K. J., Fey, A., Zacharaias, N., Russell, J. L., Ma, C., deVegt, C., Reynolds, J., Jauncey, D., Archinal, B., Carter, M. S., Corbin, T. E., Eubanks, T. M., Florkowski, D. R., Hall, D. M., McCarthy, D., McCulloch, P. M., King, E. A., Nicolson, G., & Shaffer, D. B., A Radio Reference Frame, 1995, AJ, 110, 880

Barry M. Lasker

Education:

Ph.D. (Astrophysical Science), 1964.
M.A. (Astrophysical Science), 1963.
B.S. (Physics, Yale University), 1961.

Professional Employment:

Astronomer, with tenure, Space Telescope Science Institute, 1981-present.

Cerro Tololo InterAmerican Observatory, La Serena, Chile, 1969-1981.

Assistant Professor of Astronomy, University of Michigan, Ann Arbor, Michigan 1967-1969.

NSF Postdoctoral Fellow, Hale Observatories, Pasadena, California, 1965-1967.

Group and Committee Memberships:

Member, American Astronomical Society

Member, International Astronomical Union

IAU Symposium Number 171, Chair of Scientific Organizing Committee

IAU Symposium Number 161, Co-Editor

Organizing Committee of IAU Working Group on Wide Field Imaging, 1990-1996

HST TAC Panel Support Scientist, Cycles 3 and 7

Editor of AURA Technical Proposal to NASA for the ST ScI, 1979-1980

David W. Latham

Education:

Ph.D. (Astronomy), Harvard University, 1970.

SB, (Mathematics), Massachusetts Institute of Technology, 1961.

Professional Employment:

Senior Astronomer, Smithsonian Astrophysical Observatory, 1998-present.

Senior Lecturer, Harvard University, 1990-present.

Associate Director, Center for Astrophysics, 1981-1989.

Astronomer, Smithsonian Astrophysical Observatory, 1965-1989.

Teaching Fellow, Lecturer, Harvard University, 1961-1989.

Recent Relevant Publications:

Latham, D. W., Mazeh, T., Stefanik, R. P., Mayor, M., & Burki, G., The Unseen Companion of HD114762: A Probable Brown Dwarf, 1989, Nature, 339, 38

Latham, D. W., Mazeh, T., Stefanik, R. P., Davis, R. J., Carney, B. W., Krymolowski, Y., Laird, J., Torres, G., & Morse, J. A., A Survey of Proper-Motion Stars. XI. Orbits for the Second 40 Spectroscopic Binaries, 1992, AJ, 104, 774

Mazeh, T., Latham, D. W., & Stefanik, R. P., Spectroscopic Orbits for Three Binaries with Low-Mass Companions and the Distribution of Secondary Masses Near the Substellar Limit, 1996, ApJ, 466, 415

Mazeh, T., Mayor, M., & Latham, D. W., Eccentricity versus Mass for Low-Mass Secondaries and Planets, 1997, ApJ, 478, 367

Latham, D. W., Radial-Velocity Searches for Low-Mass Companions Orbiting Solar-Type Stars, 1997, ASPC, 119, 19

Latham, D. W., Stefanik, R. P., Mazeh, T., Torres, G., & Carney, B. W., Low-Mass Companions Found in a Large Radial-Velocity Survey, 1998, ASPC, 134, 178

Sartoretti, P., Brown, R. A., & Latham, D. W., A Search for Substellar Companions around Nine Weak-lined T-Tauri Stars with the Planetary Camera 2 of the Hubble Space Telescope, 1998, A&A, 334, 592

Mazeh, T., Goldberg, D., & Latham, D. W., Distribution of Extrasolar Planet-Candidates and Spectroscopic-Binary Low-Mass Companions, 1998, ApJL, in press.

David G. Monet

Education:

Ph.D. (Astronomy and Astrophysics), University of Chicago, 1979.

B.Sc. (Physics and Astronomy), Case Western Reserve University, 1973.

Professional Employment:

Post-Doctoral Research Associate, Kitt Peak National Observatory 1979-1981.

Las Campanas Observatory Fellow, Mount Wilson and Las Campanas Observatory, 1981-1984.

Astronomer, U.S. Naval Observatory Flagstaff Station, 1984 - Present

Honors and Awards:

J.J. Nassau Prize, Case Western Reserve University, 1973.

Special Achievement Awards, U.S. Naval Observatory, 1985, 1986, 1988, 1990, 1994-1998.

Superintendent's Award, U.S. Naval Observatory (1986).

Newcomb Award, U.S. Naval Observatory (1992).

Asteroid 5952 (1987 EV) Davemonet (1996).

Recent Relevant Publications:

Monet, D. G, et al. 1996, USNO-A1.0 (USNO, Washington, D.C.)

Monet, D. G., Dahn, C. C., Vrba, F. J., Harris, H. C., Pier, J. R., Luginbuhl, C. B., & Ables, H. D., U.S. Naval Observatory CCD Parallaxes Of Faint Stars. I. Program Description And First Results, 1992, AJ, 103, 638

James D. Phillips

Education:

Ph.D. (Physics), Stanford University, 1983.

B.Sc. (Physics), University of Michigan, 1975.

Professional Employment:

Physicist, Harvard-Smithsonian Center for Astrophysics (CfA), Cambridge, MA, 1988-present.

Research Assistant, Research Associate, and Lecturer, Stanford University, 1977-1988.

Research Assistant, University of Michigan, 1976.

Research Intern, Argonne National Laboratory, 1974.

Honors and Awards:

National Science Foundation Graduate Fellowship.

Group and Committee Memberships:

Member, Sigma Xi

Member, American Physical Society

Optical Society of America, New England Chapter, Program Chair

Science by Mail program of the Boston Museum of Science

Judge, Lexington High School Science Fair, 1990-present

Recent Relevant Publications:

U.S. Patent issued for picometer laser distance gauge, three Physical Review Letters articles, 24 proceedings papers, 8 abstracts.

Robert D. Reasenberg

Education:

Ph.D. (Physics), Brown University, 1970

B.S. (Physics), Polytechnic University, 1963

Professional Employment:

Research Associate, M.I.T., 1969-1971.

Research Staff Member, M.I.T., 1971-1979.

Principal Research Scientist, M.I.T., 1980-1982.

Research Affiliate, M.I.T., 1983-1984.

Physicist, Smithsonian Astrophysical Observatory, 1982-present.

Lecturer, International School of Cosmology and Gravitation: 5th Course, 1977; 6th Course, 1979; 8th Course, 1982; 9th Course, 1985; 10th Course, 1987.

Group and Committee Memberships:

Member, Sigma Xi

Member, American Association for the Advancement of Science

Member, American Astronomical Society

Member, American Physical Society

Member, International Astronomical Union

Member, International Society on General Relativity and Gravitation

Member, Mariner 9 Celestial Mechanics Team

Member, Mariner Venus/Mercury Radio Science Team

Member, Viking Radio Science Team.

Member, Pioneer/Venus Orbiter Science Steering Group

Chairman, Committee on Gravitation and Relativity, Starprobe Mission, 1980-1981

Consultant to NASA Ames Research Center, Evaluation of advanced high-precision spaceborne astrometric instruments, 1981-1983

Member, Planetary Systems Science Working Group, renamed TOPSSWG, 1988-1992

Member, Ad Hoc Committee on Gravitation Physics and Astronomy, 1989-1991

Member, Interferometry Panel, Astronomy and Astrophysics Survey, 1989-1990

Chair, Road Map Team (one of three) for the Exploration of Neighboring Planetary Systems, 1995-1996

Member at Large, Space Interferometry Mission Science Working Group, 1996-present

Member, Science Advisory Committee for Gravity Probe-B, 1998-present

Siegfried Röser

Education:

Doctor rer. nat., (Astronomy), Universität Heidelberg, 1976.

Diplom-Mathematiker, Mathematics (Master's degree), Universität Heidelberg, 1972.

Professional Employment:

Astronomer, Astronomisches Rechen-Institut, Heidelberg, 1979-present.

Astronomer, Max-Planck-Institut für Kernphysik, Heidelberg, 1976-1979.

Group and Committee Memberships:

IAU: Commission 24. Member, The Organizing Committee, 1997-2000

ESA: Member, Science Advisory Group GAIA, 1997-1998

DLR: Member, Space Interferometry Working Group (ISWG), 1995-1998

Member (Task Leader) of the FAST Committee for the reduction of data of the ESA-mission HIPPARCOS, 1981-1996

Recent Relevant Publications:

Röser, S., Morrison, J., Bucciarelli, B., Lasker, B., & McLean, B. V., Contents, Test Results, and Data Availability for GSC 1.2., 1997, IAU Symposium No. 179, Eds. B. J. McLean, D. A. Golombek, J. E. Hayes, H. E. Payne. Kluwer, Dordrecht 1997, p.420. GSC 1.2

Bastian, U., Röser, S., Høg, E., Mandel, H., Seifert, W., Wagner, S., Quirrenbach, A., Schalinski, C., Schilbach, E., & Wicenec, A., DIVA—An Interferometric Minisatellite for Astometry and Photometry, 1996, Astronomische Nachrichten, 317, 281

Lindegren, L., Röser, S., Schrijver, H., Lattanzi, M. G., van Leeuwen, F., Perryman, M. A. C., Bernacca, P. L., Falin, J. L., Froeschlé, M., Kovalevsky, J., Lenhardt, H., & Mignard, F., A Comparison of Ground-Based Stellar Positions and Proper Motions with Provisional Hipparcos Results, 1995, Astronomy & Astrophysics, 304, 44

Röser, S. & Bastian, U., PPM Star Catalogue. Positions and Proper Motions for 181731 Stars North of -2.5 Degrees Declination for Equinox and Epoch J2000.0. Spektrum Akademischer Verlag, Heidelberg, Berlin, New York, 1991

Philip Michael Sadler

Education:

Ed.D., Harvard Graduate School of Education, 1992.

Ed.M., Harvard Graduate School of Education, 1974.

B.S., Physics, Massachusetts Institute of Technology, 1973.

Professional Employment:

Harvard University Graduate School of Education, Cambridge, MA, Assistant Professor, 9/1992-present; Instructor, 1991.

Frances W. Wright Lecturer on Navigation, Harvard University, 1990-present.

Director, Science Education Department, Harvard-Smithsonian Center for Astrophysics, 1/92-present.

Co-investigator or project manager for these NSF Education Projects:

❏ DESIGNS, middle school engineering curriculum, 1995-present.

❏ Misconception Video Project, documentary films on student conceptions in science, 1993-present.

❏ MicroObservatory, development of low-cost electronic telescope for school use, 1989-present.

❏ ARIES, elementary school curriculum development in astronomy, 1992-1995.

❏ InSIGHT, development of advanced simulations for introductory physics, 1989-1995.

❏ SPICA, summer institutes to train astronomy workshop leaders, 1989-1991.

❏ Project STAR, development of high school level astronomy course, 1985-1991.

Vice President and Co-Founder, Peripheral and Software Marketing, Inc., Newton, MA, 10/82-12/85.

Vice President and Co-Founder, Computer Products Marketing, Inc., Newton, MA, 8/81-12/85.

Learning Technologies Inc., Cambridge, MA, President, 7/77-9/85 (on leave 9/85-1/92); Chairman, 7/77-present.

Teacher (grades 7 and 8) and Science Coordinator, Carroll School, Lincoln, MA, 9/74-6/77.

Honors and Awards:

Winner for Mouselab, Computers in Physics, American Institute of Physics (shared), 1994.

Silver Plaque Award for “Sun, Moon, Stars,” Industrial Film & Video Festival (shared), 1992.

Honorable Mention for MBL Spectrometer, Computers in Physics, American Inst. of Physics (shared), 1992.

Winner for Wavemaker, Computers in Physics, American Inst. of Physics (shared), 1991.

Margaret Noble Address, Middle Atlantic Planetarium Society, May 1991.

Recent Relevant Publications:

Walton, Schey, Christie, Garfunkel, & Sadler. Computer and Laboratory Calculus, Educational Development Center, Newton, MA, 1975.

Coyle, Gregory, Luzader, Sadler, & Shapiro. Project STAR. The Universe in Your Hands, Cambridge: Harvard-Smithsonian Center for Astrophysics, 1990.

Sadler, P. M., Misconceptions in Astronomy, Proceedings of the Second International Seminar, Misconceptions and Educational Strategies in Science and Mathematics. Cornell University, Vol. 3; 1987.

Sadler, P. M. & Luzader, W., Science Teaching through its Astronomical Roots, The Teaching of Astronomy, Cambridge: Cambridge University Press, 1990, pp. 257-76.

Sadler, P. M., SPICA, A National Program of Astronomy Workshops, Proceedings of the International Planetarium Society, Borlange Conference, 1990.

Sadler, P. M., Projecting Spectra for Classroom Investigations. The Physics Teacher, College Park, MD: American Association of Physics Teachers, MD, 29:7, 1991, pp. 423-427.

Lightman, A. & Sadler, P. M., Teacher Predictions versus Actual Student Gains. The Physics Teacher. College Park, MD: American Association of Physics Teachers, 31:3, 1993, pp. 162-167.

Sadler, P. M. Teachers Misconceptions of their Students’ Learning. Proceedings of the Third International Seminar, Misconceptions and Educational Strategies in Science and Mathematics. Cornell University, 1993.

Sadler, P. M., Astronomy’s Conceptual Hierarchy, Proceedings of the Astronomy Education Meeting, San Francisco: Astronomical Society of the Pacific, 6/23-25/95, in press.

Allan Sandage

Education:

Ph.D., Astronomy, California Institute of Technology, 1953.

A.B., Physics, University of Illinois, 1948.

Professional Employment:

Research Staff Astronomer Emeritus, The Observatories of the Carnegie Institution of Washington.

Homewood Professor of Physics, The Johns Hopkins University, 1987-1989.

Visiting Astronomer, University of Basel, Switzerland, 1985-1992; Visiting Processor, 1994.

Fulbright Scholar at the Australian National University in Astronomy-Mount Stromolo National Observatory, 1969-1971.

Group Memberships:

American Philosophical Society

Lincei National academy (Rome)

Publications:

Five books, 350 research papers, mostly in ApJ, AJ, and PASP. Associate editor of ARA&A, 1990-present.

P. Kenneth Seidelmann

Education:

Ph.D., Dynamical Astronomy, University of Cincinnati, 1968.

M.S., Science, University of Cincinnati, 1962.

B.A., Electrical Engineering, University of Cincinnati, 1960.

Professional Employment:

Research and Development Coordinator, U.S. Army Missile Command, 1963-1965.

Astronomer, Nautical Almanac Office of U.S. Naval Observatory, 1965-1976.

Director of the Nautical Almanac Office, U.S. Naval Observatory, 1976-1990.

Director of the Orbital Mechanics Department, 1990-1994.

Associate Director for Astrometry and Director of the Astrometry Directorate, U.S. Naval Observatory, 1994.

Lecturer, Catholic University of America, 1966.

Visiting Adjunct Professor, University of Maryland, 1973-present.

Honors and Awards and Accomplishments:

Distinguished Alumnae Award, College of Engineering, University of Cincinnati.

Devised and calculated the accurate analemma for the Longwood Gardens Sundial.

Prepared star chart for the Einstein monument on the grounds of the National Academy of Sciences.

Group and Committee Memberships:

Chairman of the Washington Section, Eastern Regional Vice President, Executive Vice President, and President, Institute of Navigation

Vice President, International Associates of Institutes of Navigation

Member, International Astronomical Union (IAU)

Member, Organizing Committee, Commission 4 on Ephemerides and Commission 7 on Celestial Mechanics

Past President, Commission 4

Chairman, IAU working groups on planetary ephemerides and nutation

Member, working groups for precession and cartographic coordinates and rotational elements of planets and satellites

Secretary, Vice Chairman, Chairman, Division on Dynamical Astronomy of the American Astronomical Society

Member, Editorial Committee for the journal Celestial Mechanics

President, Celestial Mechanics Institute

Member, Investigation Definition Team for the Wide Field/Planetary Camera for Space Telescope

Co-Discoverer of a satellite of Saturn

Recipient, Norman P. Hays Award of the Institute of Navigation

Michael Shao

Education:

Ph.D. Massachusetts Institute of Technology, 1978.

B.S. Massachusetts Institute of Technology, 1971.

Professional Employment:

Director, Interferometry Center of Excellence, JPL Oversight of the Interferometry Programs and Development of Supporting Infrastructure, 1996-Present.

Supervisor, Spatial Interferometry Group, JPL Research in Stellar Interferometry, 1984-1996.

Astrophysicist, Smithsonian Astrophysical Observatory, Research in Stellar Interferometry, 1981-1984.

Postdoctoral Associate, Massachusetts Institute of Technology, Research in Interferometer Astrometry, 1978-1981.

Group and Committee Memberships:

Member, American Astronomical Society

Fellow, Optical Society of America

Member, NASA code SZ Space Interferometry Science Working Group

Member, AIAA Technical Committee on Space Science and Astronomy

Member, NASA SL TOPSSWG/PSSWG Towards Other Planetary Systems Science Working Group (89-92)

Member, NASA SL Planetary Astronomy Committee (93)

Member, NSF ACAS subcommittee on Ground O/IR Astronomy (90)

Member, AASC (Bahcall) Panel on Interferometry (90)

Member, AASC (Bahcall) Panel on UV optical from Space

Member, NASA Astrophysical Subcommittee, 1992-1996.

Member, Celestial Mechanics Institute, 1991-1996

Chairperson, NASA Committee on Gravitation Physics and Astronomy, 1989-1990

Chairperson, NASA Astrophysics Subcommittee, 1988-1992

Member, NASA Advisory Council, 1987-1990

Member, National Science Resources Center Advisory Board, 1987-1990

Member, Technical Oversight Committee of the National Earth Orientation Service, 1986-present

Member, VNU Science Press Advisory Board for Books "Topics in Astronomy and Astrophysics," 1985-present

Member, AAS Tinsley Prize Committee, 1985-1988

Member, NASA Astrophysics Subcommittee, 1985-1987

Member, NRAO VLBA Advisory Committee, 1985-1987

Co-Chairman, Northeast Radio Observatory Corporation Board of Trustees, 1985-present

Board Study "Major Directions for Space Science: 1995-2015," 1984-1986

Member, Task Group on Astronomy and Astrophysics of National Research Council Space Science

Member, NAS Watson Medal Selection Committee, 1984

Member, NSF Astronomy Advisory Committee, 1983-1986

Vice-Chairman, Northeast Radio Observatory Corporation Board of Trustees, 1983-1985

Member, Committee on Operations and Policy, Haystack Observatory, 1982-present

Fellow, American Association for the Advancement of Science

Member, American Astronomical Society

Fellow, American Geophysical Union

Fellow, American Physical Society

Member, International Astronomical Union

Member, AAS Pierce/Warner Prize Committee, 1992-1994

Recent Publications:

Colavita, M., Shao, M., Hines, B. E., et al., ASEPS-O Testbed Interferometer, 1994, Proc. SPIE, 2200, 89-97

Colavita, M., Shao, M., & Rayman, M. D., Orbiting Stellar Interferometer for Astrometry and Imaging, 1993, Applied Optics, 32, 1789-1797

Colavita, M. & Shao, M., Potential of Long-Baseline Infrared Interferometry for Narrow-Angle Astrometry, 1992, A&A, 262, 353-358

Colavita, M. & Shao, M., Long-Baseline Optical and Infrared Stellar Interferometry, 1992, ARA&A, 30, 457-498

Irwin I. Shapiro

Education:

Ph.D. (Physics), Harvard University, 1955.

A.M. (Physics), Harvard University, 1951.

A.B. (Mathematics), Highest Honors, Cornell University, 1950.

Employment:

Staff member, M.I.T. Lincoln Laboratory, 1954-1970.

Professor of Geophysics and Physics, M.I.T., 1967-1980.

Schlumberger Professor, M.I.T., 1980-1985.

Schlumberger Professor Emeritus, M.I.T., 1985-present.

Senior Scientist, Smithsonian Astrophysical Observatory, 1982-present.

Paine Professor of Practical Astronomy and Professor of Physics, Harvard University, 1982-1997.

Director, Harvard-Smithsonian Center for Astrophysics, 1983-present.

Timken University Professor, Harvard University, 1997-present.

Honors and Awards:

Albert A. Michelson Medal of the Franklin Institute, 1975.

Benjamin Apthorp Gould Prize of the National Academy of Sciences, 1979.

John Simon Guggenheim Fellowship, 1982.

New York Academy of Sciences Award in Physical and Mathematical Sciences, 1982.

Dannie Heineman Award of the American Astronomical Society, 1987.

Dirk Brouwer Award of the American Astronomical Society, 1987.

Charles A. Whitten Medal of the American Geophysical Union, 1991.

NASA Group Achievement Award, 1994.

William Bowie Medal of the American Geophysical Union, 1993.

Einstein Medal, 1994.

Gerard P. Kuiper Prize of the American Astronomical Society, 1997

Honor and Professional Societies:

Member, Phi Beta Kappa,

Member, Phi Kappa Phi

Member, Sigma Xi

Member, American Academy of Arts and Sciences, 1969

Member, National Academy of Sciences, 1974

American Association for the Advancement of Science

American Astronautical Society

American Geophysical Union (Fellow)

American Physical Society (Fellow)

Internaional Astronomical Union

Current Research:

Radio and radar techniques' application to astrometry, astrophysics, geophysics, planetary physics, and tests of the theory of gravitation.

Publications:

Over 250 publications authored or coauthored on scientifc research and education.

Sean E. Urban

Education:

B.S. (Astronomy), University of Maryland, 1985.

Professional Employment:

Astronomer, Astrometry, U.S. Naval Observatory, 1985-present.

Honors and Professional Societies:

Member, Americal Astronomical Society (AAS)

Member, Division of Dynamical Astronomy of the AAS

Member, International Astronomical Union (commision 8)

Chairman, IAU Working Group on Densification of the Optical Reference Frame

Recent Relevant Publications:

Urban, S. E., Corbin, T. E., & Wycoff, G. L., The ACT Reference Catalog, 1998, ApJ, 115, 2161

Urban, S. E., Corbin, T. E., Wycoff, G. W., Martin, J. C., Jackson, E. S, Zacharias, M. I., & Hall, D. M., The AC 2000: The Astrographic Catalogue on the System of the Hipparcos Catalogue, 1998, AJ, 115, 1212

Zacharias, N., Hoeg, E., Urban, S. E. and Corbin, T. E., Comparing the Tycho Catalogue with CCD Astrograph Observations, 1997, ESA SP, 121

Germain, M., Urban, S., Murison, M., Seidelmann, P. K., Johnston, K. J., Shao, M., Fanson, J., Yu, J., Davinic, N., & Rickard, L. J., Fizeau Astrometric Mapping Explorer, 1997, ASP Conf. Ser., 119, 273

Corbin, T. & Urban, S., The Astrographic Catalog Reference Stars, 1991, NASA, NSSDC 91-10

William F. van Altena

Education:

Ph.D. (University of California, Berkeley) (Lick Observatory), 1966.

B.A. (University of California, Berkeley), 1962.

Professional Employment:

Instructor to Assoc. Prof., University of Chicago, 1966-1974.

Director, Yerkes Observatory, University of Chicago, 1972-1974.

Professor, Department of Astronomy, Yale University, 1974.

President, Yale Southern Observatory, 1975-present.

Chairman, Department of Astronomy, Yale University, 1975-1981.

Vice President and President, International Astronomical Union, Commission 24 (Photographic Astrometry), 1986-1991.

President, WIYN Observatory Board of Directors, 1996-present.

Visiting Professor, Vatican Observatory (Rome), June-August 1977; Chinese Academy of Sciences, May 1991; University of Barcelona, Spain, April-August 1992; National Astronomical Observatory of Japan, January-May 1995.

National Academy of Sciences Astronomy Decade Review panels, 1969-1971, 1979-1980.

Group and Committee Memberships:

Corresponding Member (elected 1997), Barcelona Academy of Arts and Sciences; Fellow AAAS.

American National Standards Institute Committee PH1-3, 1970-1990.

Space Telescope Astrometry Instrument Definition Team Leader 1972-1976.

Hubble Space Telescope Astrometry Science Team, 1977-present.

AURA Board of Directors, 1972-1974.

WIYN Board of Directors and SAC, 1996-present.

Member of various AURA, NSF, and Space Telescope Science Institute Visiting and Users Committees.

HST General Observer Proposal Review Panels for Cycles 1, 1-Revision, and 2.

NSF Advisory Committee for Astronomical Sciences (ACAST), 1991-1993.

Member of NASA Space Interferometer Mission Science Working Group, 1996-present.

David Van Buren

Education:

Ph.D. (University of California, Berkeley), 1983.

Professional Employment:

Senior Research Fellow, Theoretical Astrophysics, California Institute of Technology, 1992.

Staff Scientist, Infrared Processing and Analysis Center, California Institute of Technology and Jet Propulsion Laboratory, 1993-present.

Group and Committee Memberships:

Member of the Space Interferometry Mission Science Working Group.

Architect for the Interferometry Science Center at Caltech/JPL.

Publications:

Van Buren, D., Terebey, S., Ressler, M., and Brundage, M., 10 Micron Search for Cool Companions, 1998, AJ, accepted.

Boden, A. F., Sao, M., & Van Buren D., Astrometric Observations of Macho Gravitational Microlensing, 1998, ApJ, 502, 538.

Terebey, S., Van Buren, D., Padgett, D., Hancock, T., & Brundage, M., A Candidate Protoplanet in Taurus, 1998, ApJ Letters, accepted.

Wade, L. A., Llilienthal, G. W., Terebey, S., Kadogawa, H., Hawarden, T. G., Rourke, K., & Van Buren, D., Mid-Infrared Optimized Resolution Spacecraft (MIRORS), 1996, Boulder Meeting on Spacecraft Technologies, Conference Proceedings.

Jarrett, T. H., Beichman, C. A., Van Buren, D., Gautier, N., Jorquera, C., & Bruce, C., Palomar Prime-Focus Infrared Cameras (PFIRCAM), 1993, Infrared Arrays: The Next Generation, McLean, I., ed. (Kluwer).

Richard H. Vassar

Education:

Ph.D. (Aeronautics and Astronautics), Stanford University.

M.S. (Aeronautics and Astronautics), Stanford University.

B.S. (Aerospace and Ocean Engineering), Virginia Polytechnic Institute and State University.

Professional Employment:

Lockheed Martin Missiles & Space, Advanced Technology Center, 1984-Present

Deputy Program Manager, Gravity Probe-B Space Vehicle Program, Cryogenic Payloads Laboratory

Program Manager, Gravity Probe-B Payload Program, Cryogenic Payloads Laboratory.

Assistant Program Manager-Technical, Gravity Probe-B Payload Program, Cryogenics Payloads Laboratory.

Chief Systems Engineer, Gravity Probe-B Payload Program, Cryogenics Payloads Laboratory.

Senior Staff Scientist, Dynamics and Control Laboratory. Lead control systems engineer on the Zenith Star program.

Member of the Technical Staff, Control Systems Engineering Department, TRW, Redondo Beach, CA, 1981-1984.

Group and Committee Memberships:

Associate Fellow, American Institute of Aeronautics and Astronautics.

Recent Relevant Publications:

Turneaure, J. P., Vassar, R. H., et al., Development of the Gravity Probe B Flight Hardware, July 1996, Conference in Birmingham, England, Advances in Space Research, 1997

Keiser, G. M.,Vassar, R. H., et al., Establishing Confidence in the Outcome of the Gravity Probe B Relativity Mission: In-Flight Calibration and Techniques for Eliminating Possible Systematic Experimental Error, Proceedings of the Fourteenth International Conference of General Relativity and Gravitation, June 1995

Keiser, G. M.,Vassar, R. H., et al., An Update on the Estimated Accuracy of the Gravity Probe B Experiment and Plans to Test for Systematic Experimental Error, Proceedings of the Thirteenth International Conference of General Relativity and Gravitation, 28 June-4 July 1992, Cordoba, Argentina

Bardas, D., Vassar, R. H., et al., The Gravity Probe-B Relativity Gyroscope Experiment: Progress on Development of the Flight Instrument, Proceedings of the Sixth Marcel Grossman Meeting on General Relativity, Kyoto, Japan, June 1991, World Scientific, Singapore)

Axelrad, P., Vassar, R. H., & B. W. Parkinson, Gravity Probe-B Orbit Modeling and Injection Requirements, AAS91-164, Proceedings of the AAS/AIAA Spaceflight Mechanics Meeting, 11-13 February 1991

Everitt, C. W. F., Vassar, R. H., et al., The Merits of Space and Cryogenic Operation in the Gravity Probe B Relativity Gyroscope Experiment, Proceedings of the First William Fairbank Meeting on Relativistic Gravitational Experiments in Space, 10-14 September 1990, Rome, Italy

Turneaure, J. P., Everitt, C. W. F., Parkinson, B. W., Vassar, R. H., et al., The Gravity Probe-B Relativity Gyroscope Experiment: Approach to a Flight Mission, Proceedings of the Fourth Marcel Grossman Meeting on General Relativity, ed. R. Ruffini, North-Holland Amsterdam, 1986, pp. 411-464

Vassar, R. H. & Sherwood, R. B., Formation keeping for a Pair of Satellites in a Circular Orbit, Journal of Guidance and Control, Vol.8, No.2, March-April 1985, pp. 235-242

Vassar, R. H., Error Analysis for the Stanford Relativity Gyroscope Experiment, SUDDAR 531, Ph.D. Dissertation, Stanford University, April 1982

Vassar, R. H., Breakwell, J. V., Everitt, C. W. F., & Van Patten, R. A., Orbit Selection for the Stanford Relativity Gyroscope Experiment, Journal of Spacecraft and Rockets, Vol.19, No.1, Jan-Feb 1982, pp. 66-71

Donald G. York

Education:

Ph.D. (University of Chicago), 1971.

B.S. (Massachusetts Institute of Technology), 1966.

Professional Employment:

Horace B. Horton Professor of Astronomy and Astrophysics, (Selected) University of Chicago, 1992-present.

Sr. Research Astronomer, Princeton University, 1979-1982.

Director, Sloan Digital Sky Survey, 1988-1997.

Director, Apache Point Observatory, 1983-present.

Honors and Awards:

NASA Public Service Award, 1976.

Group and Committee Memberships:

Member, American Astronomical Society International Astronomical Union.

Lectures:

Numerous lectureships and colloquia, world wide, since 1973.

D. References List

Bahcall, J. N. 1984, "K-giants and the total amount of matter near the Sun," ApJ, 287, 926-944

Bahcall, J. N., Flynn, C., and Gould, A. 1992, "Local dark matter from a carefully selected sample," Ap. J. 389, 234-250

Ball, B. B., Coyle, H. P., and Shapiro, I. I. Project SPICA: Dubuque: Kendall/Hunt.

Bastian, U., Gilmore, G., Halbwachs, J. L., Hog, E., Knude, J., Kovalevsky, J., Labeyrie, A., van Leeuwen, F., Lindegren, L., Pel, P. W., Schrijver, H., Stabell, R., and Thejll, P. 1993, "ROEMER, Proposal for the Third Medium Size ESA Mission (M3)," Lund (available from L. Lindegren on request)

Casertano, S. 1998, private communication

Coyle, H., Gregory, B., Sadler, P., and Shapiro, I. (1992). Project STAR. Dubuque: Kendall/Hunt

Crèzè, M., Chereul, E., Bienayme, O., and Pichon, C. 1998, A&A, 329, 920

de Vegt, C. and Ebner, H., 1974, MNRAS, 167, 169

ESA, 1997, SP-1200 vol 3

Evans, N. R. 1992, "New calibration for the Cepheid period-luminosity relation," ApJ, 389, 657-664

Evans, N. R. 1995, "The mass ratios of Cepheid binaries," ApJ, 445, 393-405

Feast, M W., and Walker, A. R. 1988, "Cepheids as distance indicators," ARA&A, 25, 345

Flynn, C. and Fuchs, D. 1994, "Density of matter in the Galactic disk," MNRAS, 270, 471-479

Gilden, D. L and Bahcall, J. N. 1985, "Sampling errors in the determination of the total amount of mass at the solar position," ApJ, 296, 240-258

Gilmore, G., Wyse, R, F. G., and Kuijken, K. 1989, "Kinematics, chemistry and structure of the Galaxy," ARA&A, 27, 555

Gould, A., Bahcall, J., and Flynn, C. 1995, "Disk M dwarf luminosity function from HST stars counts," ApJ (submitted)

Gould, A. and Popowski, P. 1998, "Systematics of RR Lyrae Statistical Parallax III: Apparent Magnitudes and Extinctions," ApJ, 508, 000 (astro-ph/9805176)

Gratton, R.G., Fusi Pecci, F., Carreta, E., Clementini, G., Corsi, C.E., Lattanzi, M. 1997, "Ages of Globular Clusters from Hipparcos Parallaxes of Local Subdwarfs," ApJ, 491, 749-771

Harvie, E., Rowe, J., Tsui, Yo-Kung J., "Performance Analysis of the GOES Trim Tab Solar Pressure Torque Angular Momentum Control"

IERS, 1996, Tech. Note 21, ed. D. McCarthy, Obs. de Paris

Jacoby, G. H., Branch, D., CiarduBo, R., Davies, R- L, Harris, W. E., Pierce, M. J., Pritchet, C. J., Tonry, J. L, and Wekh, D. L. 1992, "A critical review of selected techniques for measuring extragalactic distances," PASP, 104, 599

Johnston, K. J., Seidelmann, P. K. et al. 1998, "Fizeau Astrometric Mapping Explorer (FAME)," in preparation

Kovalevsky, J. L. et al., 1992, A&A, 258, 7

Kuijken, K. and Gilmore, G. 1989, "The Mass-Distribution in the Galactic Disk. 3. The Local Volume Mass Density," Ann. Rev. Astron., 27, 555-627

Kuijken, K. and Gilmore, G. 1991, "The galactic disk surface mass density and the Galactic force at Z=1.1 kiloparsecs," ApJ, 367, L9-Ll3

Lindegren, L. et al., 1992, A&A, 258, 18

Lindegren, L., Perryman, M. A. C., and Loiseau, S. 1995, "Global Astrometric Interferometer for Astrophysics (GAIA)," SPIE Proceedings 2477, 91-103

Madore, B. F. and Freedman, W. L. 1991, "The Cepheid distance scale," P.A.S.P., 103, 933-957

Mazeh, Goldberg, and Latham, 1998, ApJL, 501, 199

Monet, D. G., Dahn, C. C.,Vrba, F. J., Harris, H. C., Pier, J. R., Luginbuhl, C. B., and Ables, H. D. 1992, "United States Naval Observatory CCD parallaxes of faint stars l: program description and first results," AJ, 103,638

Perryman, M. A. C. et al., 1989, The Hipparcos Mission, ESA SP-1111 vol. 3

Perryman, M. A. C. et al. 1997, The Hipparcos and Tycho Catalogues, ESA SP-1200

Phillips, J.D. and Reasenberg, R.D., 1998, "Optical System for an Astrometric Survey from Space," SPIE 3356, (in press)

Popowski, P. and Gould, A. 1998, "The RR Lyrae Distance Scale" in "Post-Hipparcos Cosmic

Candles," in press, F. Caputo and A. Heck, eds., Kluwer

Reasenberg, R.D., 1996, "The Astrometric Information Rate with a Central Obscuration in a Rectangular Aperture," SAO Technical Memorandum

Reasenberg, R.D., and Phillips, J.D., 1998, "Design of a Spaceborne Astrometric Survey Instrument," SPIE 3356, (in press)

Reid, I.N. 1997, "Younger and Brighter—New Distances to Globular Clusters Based on Hipparcos Parallax Measurements of Local Subdwarfs," AJ, 114, 161-179

Röser, S., Bastian, U., de Boer, K. S., Hog, E., Röser, H. P., Schalinski, C., Schilbach, E., de Vegt, C., and Wagner, S. 1997 "DIVA - Towards Microarcsecond Global Astrometry," Proceedings of the Hipparcos Venice '97 Symposium, Venice, May (13-16) 1997, http://astro.estec.esa.nl/Hipparcos/venice.html#session12

Schneps, M. H., and Sadler, P. M. (1988). A Private Universe. In Pyramid Films

Urban, S., Corbin T., and Wycoff G., 1998, "The ACT Reference Catalog." A.J. 115, 2161

van den Bergh, S. 1995, "On the discrepancy between the Cepheid and RR Lyrae distance scales," ApJ, 446, 39-43

Washwell, E. R., ed., 1996, "GOES-8 and Beyond", SPIE Proceedings 2812, 741-752

Winter, L., 1998, private communication from PH.D thesis

E. Acronyms List

Acronym	Definition
ADC	Analog to Digital Convertor
ADCS	Attitude Determination & Control Subsystem
AKM	Apogee Kick Motor
BER	Bit Error Rate
C	Centigrade
C^2	Command and Control
CCA	Circuit Card Assembly
CCD	Charge Coupled Device
CCSDS	Consultative Committee for Space Data Systems
cm	centimeter
COTS	Commercial Off-the-Shelf
CT&DH	Command, Telemetry, and Data Handling
CTE	Coefficient of Thermal Expansion
DHU	Data Handling Unit
DOD	Department of Defense
DRAM	Dynamic Random Access Memory
E_b/N_o	Signal Energy per Bit/One-Sided White Noise Density
EDAC	Error Detected and Corrected
EE&C	Engineering Evaluation and Checkout
EEE	Electrical, Electronic, and Electromechanical
ELV	Expendable Launch Vehicle
EMC	Electromagnetic Compatibility
EMI	Electromagnetic Interference
EOL	End of Life
EPS	Electrical Power Subsystem
E-W	East-West
FAME	Full-Sky Astrometric Mapping Explorer
FEP	Front-End Processor
FOT	Flight Operations Team
FOV	Field of View
FPGA	Field Programmable Gate Array
FSW	Flight Software
G&A	General and Administrative
GEO	Geosynchronous Earth Orbit
GNC	Guidance, Navigation, and Control
GrCyn	Graphite Cyanate
GSE	Ground Support Equipment
GTO	Geosynchronous Transfer Orbit
GUI	Graphical User Interface
hrs	hours
H/W	Hardware
I/F	Interfaces
ICD	Interface Control Document
ICRS	International Celestial Reference System
IPAC	Infrared Processing and Analysis Center
IPDT	Integrated Product Development Team
IRU	Inertial Reference Unit
ISC	Integrated Spacecraft Controller
ISV	Integrated Space Vehicle

Acronym	Definition
K	Kelvin
kg	Kilograms
L/H	Left Hand
kpc	Kiloparsecs
L/V	Launch Vehicle
LAAN	Longitude of the Ascending Node
LAST	LMFS Autonomous Star Tracker
LEO	Low Earth Orbit
LM	Lockheed Martin
LMFS	Lockheed Martin Fairchild Systems
LMMS	Lockheed Martin Missiles and Space
mag	magnitude
m	meter
mas	milliarcsecond
min	minute
MIPR	Military Interdepartmental Procurement Request
Mjup	Mass of Jupiter
mK	milliKelvin
mm	millimeter
MLI	Multi-Layered Insulation
MO&DA	Mission Operations and Data Analysis
MOTS	Modified Off-the-Shelf
MPP	Multi-Phase Pinned
M_v	Absolute Visual Magnitude
NASCOM	NASA Communications
NGST	Next Generation Space Telescope
N-S	North-South
OD	Orbit Determination
OTS	Off-the-Shelf
pc	parsec
PAF	Provided Instrument Attachment Fitting
PDCU	Power Distribution and Control Unit
PE	Project Engineer
PI	Principal Investigator
PM	Project Manager
PRN	Pseudo-Random Noise
PSF	Point Spread Function
P_s	Probability of Success
QA	Quality Assurance
RAAN	Right Ascension of the Ascending Node
RCS	Reaction Control System
RF	Radio Frequency
R/H	Right Hand
rms	root-mean square
RPM	Revolutions per Minute
RSDO	Rapid Spacecraft Development Office
S/C	Spacecraft
S/V	Space Vehicle
S/W	Software
SAO	Smithsonian Astrophysical Observatory

Acronym	Definition
SB	Small Business
SCL	Spacecraft Command Language
SDB	Small, Disadvantaged Business
SEE	Single Event Effects
SED	Science Education Department
SIM	Space Interferometry Mission
SLOC	Source Lines of Code
SOW	Statement of Work
SPV	Single Pressure Cell
SRM	Solid Rocket Motor
SS	Sun Sensor
SSD	Space Sciences Division
SSDR	Solid State Data Recorder
ST	Star Tracker
STDN	Space Tracking and Data Network

Acronym	Definition
STEX	Space Technology Experiment
TCS	Thermal Control Subsystem
TDI	Time Delay Integration
TID	Total Ionizing Dose
TMC	Total Mission Cost
TPF	Terrestrial Planet Finder
TVAC	Thermal-Vacuum
UCC	USNO Control Center
ULE™	Ultra-Low Expansion Glass (Corning, Inc.)
USNO	United States Naval Observatory
V	Apparent Visual Magnitude
W	Watt
μas	Microarcseconds
ξ	Angle between the Sun direction and the nominal axis of rotation